(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 July 2003 (24.07.2003)

PCT

(10) International Publication Number
WO 03/060447 A1

(51) International Patent Classification[7]: G01J 5/10, 5/00, H01L 21/00

(21) International Application Number: PCT/CA02/01987

(22) International Filing Date: 23 December 2002 (23.12.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/342,115 26 December 2001 (26.12.2001) US

(71) Applicant (for all designated States except US): VORTEK INDUSRIES LTD. [CA/CA]; 605 West Kent Avenue, Vancouver, British Columbia V6P 6T7 (CA).

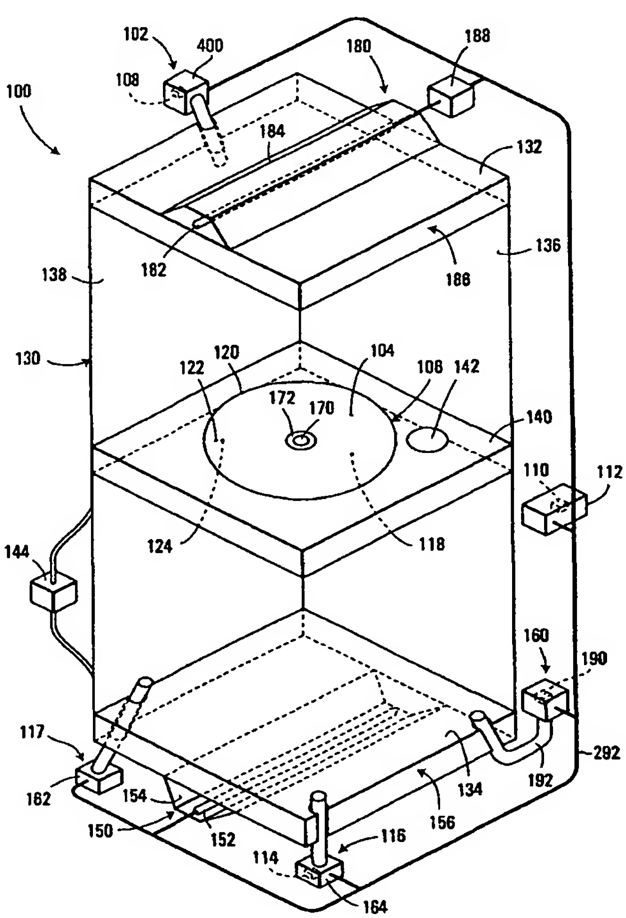
(72) Inventors; and
(75) Inventors/Applicants (for US only): CAMM, David, Malcolm [CA/CA]; 3775 West 14th Avenue, Vancouver, British Columbia V5R 2W8 (CA). KERVIN, Shawna [CA/CA]; 1432 10th Avenue, #303, Vancouver, British Columbia V6H 1J9 (CA). LEFRANCOIS, Marcel, Edmond [CA/CA]; 49 Capistrano Drive, Dartmouth, Nova Scotia, B2X 3N8 (CA). STUART, Greg [CA/CA]; 6455 Willingdon Avenue, #905, Burnaby, British Columbia V5H 4E4 (CA).

(74) Agents: FERANCE, Stephen, J. et al.; Fetherstonhaugh & Co., 650 West Georgia Street, Suite 2200, Box 11560, Vancouver Centre, Vancouver, British Columbia V6B 4N8 (CA).

(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,

[Continued on next page]

(54) Title: TEMPERATURE MEASUREMENT AND HEAT-TREATING METHODS AND SYSTEMS



(57) Abstract: Temperature measurement and heat-treating methods and systems. One method includes measuring a present intensity of radiation thermally emitted from a first surface of a workpiece, and identifying a present temperature of the first surface in response to the present intensity and at least one previous thermal property of the first surface. Preferably, the workpiece includes a semiconductor wafer, and the first and second surfaces respectively include device and substrate sides thereof. The present temperature of the device side is preferably identified while the device side is being irradiated, e.g. by an irradiance flash having a duration less than a thermal conduction time of the wafer. The device side temperature may be identified in response to a previous device side temperature, which may be identified in response to a previous temperature of the substrate side unequal to the previous device side temperature, and a temperature history of the wafer.

WO 03/060447 A1

GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declaration under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)*

Published:

— *with international search report*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

TEMPERATURE MEASUREMENT AND HEAT-TREATING METHODS AND SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of priority from United States patent application serial number 60/342,115 filed December 26, 2001, which is incorporated herein by reference.

FIELD OF THE INVENTION

Aspects of the present invention relate to methods and systems for temperature measurement. Further aspects of the invention relate to methods and systems for heat-treating a workpiece.

BACKGROUND OF THE INVENTION

In some applications, it is necessary to determine the temperature of a workpiece whose temperature is difficult to directly measure. For example, where the workpiece is a semiconductor wafer, although the temperature of a substrate side of the wafer may often be measured directly, it is not possible to accurately directly measure the temperature of the device side of the wafer, as the non-uniform patterning of devices on the device side gives rise to significant variations in both scattering and emissivity from location to location across the device side, resulting in significant temperature measurement errors.

In the past, this did not pose a significant problem, as many rapid thermal processing cycles involved heating the substrate side of the wafer at heating or ramp rates that were slow compared to a thermal conduction time through the wafer (typically 10 - 15 milliseconds), so that the temperature of a given location on the device side could be presumed to equal the temperature of the corresponding opposing location on the substrate side, and the errors resulting from such a presumption were not critical for

the purpose of achieving performance requirements applicable at that time (which are now quickly becoming obsolete).

However, these conventional techniques cannot produce sufficiently shallow junctions to comply with current and upcoming industry requirements. A new technique to address this difficulty is disclosed in pending Patent Cooperation Treaty application publication numbers WO 02/47143 and WO 02/47123 (which are incorporated herein by reference), and involves pre-heating the entire wafer to an intermediate temperature by irradiating the substrate side at a ramp rate slower than the thermal conduction rate through the wafer, then heating the device side of the wafer at a rate much faster than the thermal conduction rate, by irradiating the device side. As an arbitrary example, the wafer may be pre-heated to an intermediate temperature such as 800 °C for example, by irradiating the substrate side with an arc lamp to heat the entire wafer at a rate such as 400 °C/second, for example. The device side may then be exposed to a high-intensity flash from a flash lamp, such as a one-millisecond flash, to heat only the device side to an annealing temperature such as 1300 °C, for example. Due to the rapid heating rate of the device side during the flash (on the order of 10^5 °C/s), the bulk of the wafer remains at the intermediate temperature, and acts as a heat sink to then cool the device side following the flash.

To minimize performance variations from wafer to wafer, it is important to ensure that each wafer is subjected to a consistently reproducible thermal process, as close as possible to an identical process from wafer to wafer. For this purpose, it would be desirable to accurately measure the temperature of the device side of the wafer during the flash, and to use such temperature measurements for feedback-control of the intensity of the flash. However, as noted, conventional methods are not adequate to accurately measure the temperature of the device side for this purpose.

Accordingly, there is a need for an improved way of measuring the temperature of a workpiece, and for an improved way of heat-treating the workpiece.

SUMMARY OF THE INVENTION

The present invention addresses the above need by providing, in accordance with a first aspect of the invention, a temperature measurement method. The method includes measuring a present intensity of radiation thermally emitted from a first surface of a workpiece. The method further includes identifying a present temperature of the first surface, in response to the present intensity and at least one previous thermal property of the first surface, at a respective previous time.

The workpiece may include a semiconductor wafer. If so, the first surface may include a device side of the wafer, and the second surface may include a substrate side of the wafer. In such an embodiment, identifying may include identifying the present temperature of the device side while the device side is being irradiated, or more particularly, while the device side is being exposed to an irradiance flash having a duration less than a thermal conduction time of the wafer. The irradiance flash may have a duration less than **10** milliseconds, such as a duration on the order of one millisecond, for example.

The method may include identifying, at the previous time, the at least one previous thermal property of the first surface. The at least one previous thermal property may include a previous temperature of the first surface, such as a previous temperature of the device side of the wafer immediately preceding commencement of the irradiance flash, for example. The at least one previous thermal property may further include a previous intensity of radiation thermally emitted from the device side immediately preceding commencement of the irradiance flash.

Thus, identifying may include identifying the present temperature of the first surface in response to the present intensity, a previous temperature of the first surface, and a previous intensity of radiation thermally emitted from the first surface at the previous time.

The previous temperature of the first surface may be identified in response to a previous temperature of a second surface of the workpiece unequal to the previous temperature of the first surface. If so, the first surface temperature may be identified in response to the previous second surface temperature and a temperature history of the workpiece. For example, the previous temperature of the second surface and the temperature history may be used to address a look-up table record.

The method may further including identifying, at the previous time, the previous temperature of the second surface. For example, the previous temperature of the second surface may be identified in response to a hemispherical reflectivity of the second surface.

The method may further include measuring the hemispherical reflectivity. This may include receiving radiation reflected by the second surface at a detector positioned sufficiently far away from the second surface to avoid obstructing the second surface from fields of view of other devices of a system in which the workpiece is located. Similarly, this may include receiving radiation reflected by the second surface at a detector positioned a distance from a center of the second surface, the distance being at least as great as one-half of the largest dimension of the workpiece.

Measuring the hemispherical reflectivity of the second surface may include measuring a directional reflectivity of the second surface, and may then include applying a scattering correction to the directional reflectivity to obtain the hemispherical reflectivity. The method may further include generating the scattering correction.

The previous temperature of the second surface may be identified in response to the hemispherical reflectivity of the second surface and radiation thermally emitted by the second surface.

The method may include repeatedly identifying and storing successive values of the previous temperature of the second surface at successive respective times, to generate the temperature history of the workpiece.

The method may also include repeatedly identifying successive values of the present temperature of the first surface in response to successive respective values of the present intensity of radiation thermally emitted by the first surface. Such values may be repeatedly identified while the first surface is being irradiated, or more particularly, while the first surface is being exposed to an irradiance flash having a duration less than a thermal conduction time of the workpiece.

Measuring the present intensity of radiation thermally emitted from the first surface may include measuring in a wavelength band in which an irradiance spectrum incident upon the first surface has negligible intensity. The method may include removing the wavelength band from the irradiance spectrum incident upon the first surface.

Similarly, measuring the directional reflectivity of the second surface may include measuring reflected intensity in an illumination wavelength band in which a heating irradiance spectrum incident upon the second surface has negligible intensity. The method may further include removing the illumination wavelength band from the heating irradiance spectrum.

In accordance with another aspect of the invention, there is provided a method of heat-treating a workpiece. The method includes a temperature measurement method such as that described in connection with the previous aspect of the invention, for example. The method further includes controlling a power of an irradiance flash incident on the first surface of the workpiece, in response to the present temperature of the first surface. This may include controlling power supplied to at least one irradiance source operable to produce the irradiance flash. Controlling power may

include activating one of a plurality of irradiance sources only if the present temperature of the first surface is less than a pre-defined threshold.

In accordance with another aspect of the invention, there is provided a temperature measurement system. The system includes a measurement device configured to measure a present intensity of radiation thermally emitted from a first surface of a workpiece. The system further includes at least one processor circuit in communication with the measurement device, the at least one processor circuit configured to identify a present temperature of the first surface, in response to the present intensity and at least one previous thermal property of the first surface.

The system may include various measurement devices, such as imaging devices and radiometers, for example, as described in greater detail herein. Such devices may include high-speed InGaAs photodiodes and/or photodiode arrays, for example. The at least one processor circuit may be configured to cooperate with the various devices of the system to carry out the methods described herein.

In accordance with another aspect of the invention, there is provided a system for heat-treating a workpiece. The system includes a temperature measurement system as described above, and further includes an irradiance system operable to expose the first surface of the workpiece to an irradiance flash incident thereon. The at least one processor circuit is configured to control a power of the irradiance flash in response to the present temperature of the first surface.

In accordance with another aspect of the invention, there is provided a temperature measurement system. The system includes means for measuring a present intensity of radiation thermally emitted from a first surface of a workpiece. The system further includes means for identifying a present temperature of the first surface, in response to the present intensity and at least one previous thermal property of the first surface at a respective previous time.

The system may further include means for carrying out various respective functions disclosed herein.

In accordance with another aspect of the invention, there is provided a system for heat-treating a workpiece. The system includes means as described above, and further includes means for controlling a power of an irradiance flash incident on the first surface of the workpiece, in response to the present temperature of the first surface.

Certain specific embodiments of the present invention may provide ways to obtain accurate temperature measurements of the device side of the wafer during the course of the flash. These accurate temperature measurements may then be used for feedback-control of the power of the flash, if desired, to ensure consistency of the flash and the resulting annealing process from wafer to wafer. Alternatively, even if such temperature measurements are not used for feedback-control, they may be useful in identifying system "drift", or inconsistencies developing between successive executions of thermal processes that are supposed to be identical. Identification of such inconsistencies at an early stage may allow the users of the system to correct the inconsistencies as they are developing, rather than processing a large number of wafers only to discover that poor reproducibility control of the thermal processing cycle has led to detrimental performance differences from wafer to wafer.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate embodiments of the invention,

Figure **1** is a perspective view of a system for temperature measurement and for heat-treating a workpiece, according to a first embodiment of the invention, shown with two vertical front-side walls removed.

Figure **2** is a block diagram of a rapid thermal processing system computer (RSC), a diagnostic illumination source, an imaging device, and a synchronization module, of the system shown in Figure **1**.

Figure **3** is a block diagram of a fast radiometer of the system shown in Figure **1**.

Figure **4** is a block diagram of an ultra-fast radiometer of the system shown in Figure **1**.

Figure **5** is a flow chart of a standard ratio routine executed by a processor circuit of the RSC shown in Figure **2**.

Figure **6** is a flow chart of a temperature monitoring and control routine executed by the processor circuit of the RSC shown in Figure **2**.

Figure **7** is a flow chart of a hemispherical reflectivity routine executed by the processor circuit shown in Figure **2**.

Figure **8** is a flow chart of a substrate temperature routine executed by a processor circuit of the fast radiometer shown in Figure **3**.

Figure **9** is a flow chart of a real-time device side temperature routine executed by a processor circuit of the ultra-fast radiometer shown in Figure **4**.

Figure **10** is a circuit diagram of a flash lamp power control circuit controlled by the processor circuit shown in Figure **4**.

Figure **11** is a circuit diagram of a flash lamp power control circuit controlled by the processor circuit shown in Figure **4**, according to a second embodiment of the invention.

Figure **12** is a circuit diagram of a flash lamp power control circuit controlled by the processor circuit shown in Figure **4**, according to a third embodiment of the invention.

Figure **13** is a perspective view of a system for temperature measurement and for heat-treating a workpiece, according to a fourth embodiment of the invention, shown with two vertical front-side walls removed.

DETAILED DESCRIPTION

Referring to Figure **1**, a temperature measurement system according to a first embodiment of the invention is shown generally at **100**. In this embodiment, the system **100** includes a measurement device **102** configured to measure a present intensity of radiation thermally emitted from a first surface **104** of a workpiece **106**. The system **100** further includes at least one processor circuit in communication with the measurement device **102**. The at least one processor circuit is configured to identify a present temperature of the first surface **104**, in response to the present intensity and at least one previous thermal property of the first surface at a respective previous time.

In this embodiment, the at least one processor circuit includes a processor circuit **108**. In the present embodiment, the processor circuit **108** is located within a housing of the measurement device **102**, although alternatively, the processor circuit may be located remotely from the measurement device if desired. In this embodiment, the at least one processor circuit also includes a processor circuit **110** located within a rapid thermal processing system computer (RSC) **112**, and a processor circuit **114** located

within a housing of an additional measurement device **116**. Alternatively, the various functions described herein may be performed by a single processor circuit if desired, or by other combinations of local and/or remote processor circuits.

As discussed in greater detail herein, in the present embodiment the at least one processor circuit is configured to identify, at the previous time, the at least one previous thermal property of the first surface **104**. More particularly, in this embodiment the at least one previous thermal property includes a previous temperature of the first surface. To achieve this, in the present embodiment the at least one processor circuit is configured to identify the previous temperature of the first surface **104** in response to a previous temperature of a second surface **118** of the workpiece **106** unequal to the previous temperature of the first surface **104** (although alternatively, in other embodiments, the previous temperature of the second surface may approximately equal the temperature of the first surface, for example, if the workpiece is pre-heated at a slower rate). More particularly, in this embodiment the at least one processor circuit is configured to identify the previous temperature of the first surface **104** in response to the previous temperature of the second surface **118** and a temperature history of the workpiece **106**. In the present embodiment, the at least one processor circuit is also configured to identify, at the previous time, the previous temperature of the second surface **118**, in response to a hemispherical reflectivity of the second surface.

<u>Rapid Thermal Processing Chamber</u>

In the present embodiment, the system **100** is also used for heat-treating the workpiece **106**. In this embodiment, the workpiece **106** includes a semiconductor wafer **120**. More particularly, in this embodiment the wafer **120** is a **300** mm diameter silicon semiconductor wafer for use in the manufacture of semiconductor chips, such as microprocessors, for example. In the present embodiment, the first surface **104** of the workpiece **106** includes a top-side or device side **122** of the wafer

120. Similarly, in this embodiment the second surface **118** of the workpiece includes a back-side or substrate side **124** of the wafer **120**.

In this embodiment, to carry out such heat-treating of the wafer **120**, the wafer is supported within a rapid thermal processing chamber **130**, which effectively acts as a selectively-absorbing chamber. In this embodiment, the chamber **130** is somewhat similar to that disclosed in commonly-owned U.S. Patent No. **6,303,411** (which is incorporated herein by reference), but includes radiation-absorbing regions both above and below the workpiece, rather than a combination of an absorptive and a reflective region. The selectively radiation-absorbing chamber **130** includes top and bottom selectively radiation-absorbing walls **132** and **134**, as well as side walls, two of which are shown at **136** and **138** and the other two of which are removed for illustrative purposes. In this embodiment, the side walls **136** and **138** (as well as the further side walls not shown) include specularly reflective diamond-turned aluminum surfaces, however, they cooperate with the top and bottom walls **132** and **134**, which include selectively absorbing water-cooled windows (discussed in greater detail below), to effectively act as radiation-absorbing regions at selected wavelengths.

In this embodiment, the chamber **130** further includes an internal wall **140** having respective cavities in which the workpiece **106** and a reference piece **142** are supported. In this embodiment, the workpiece is supported in its cavity by a plurality of quartz pins (not shown). If desired, the quartz pins may be provided in conjunction with a support system (not shown, not part of this invention), for supporting the workpiece in a manner such as those described in a commonly-owned United States provisional patent application being filed approximately concurrently with the present application, entitled "Methods and Systems for Supporting a Workpiece and for Heat-Treating the Workpiece", in the names of inventors Camm, Sempere, Kaludjercic, Stuart, Bumbulovic, and Rudolph.

The internal wall **140** may be either radiation-absorbing or reflectivc, depending on the particular application, with the reflective surface being more energy-efficient, but a radiation-absorbing surface resulting in greater uniformity of heating. Alternatively, a compromise between these extremes may be provided, such as a partly reflective, partly absorptive surface, such as anodized aluminum, for example. Similarly, if desired, the various reflective surfaces of the chamber **130** may be replaced by fully or partly radiation-absorbing surfaces. All of the surfaces of the chamber are preferably cooled via a cooling system **144**, which in this embodiment includes a circulated water cooling system.

In this embodiment, the reference piece **142** is a small diamond-turned, specularly reflective aluminum mirror. Alternatively, the reference piece may be made of a silicon semiconductor material similar to that of the wafer **120**, but in such a case, the reference piece **142** would preferably be relatively homogeneous, and would not include a device side. Alternatively, other types of reference pieces may be substituted.

In this embodiment, the system **100** further includes a pre-heating device **150** for pre-heating the wafer **120**. In this embodiment the pre-heating device **150** includes a high-intensity arc lamp **152** and a reflector system **154** disposed beneath the bottom wall **134** of the chamber **130**. In this embodiment, the bottom wall **134** effectively includes a filter through which the arc lamp **152** and the reflector system **154** of the pre-heating device **150** are operable to project electromagnetic radiation to heat the wafer **120**. More particularly, in this embodiment the bottom wall **134** includes a water-cooled window **156**. More particularly still, in this embodiment the water-cooled window **156** includes two parallel spaced-apart quartz panes defining a cooling channel therebetween, through which water is pumped by the cooling system **144**.

As water tends to absorbs infrared radiation at **1450** nm, and quartz also tends to absorb longer-wavelength infrared, the water-cooled window **156** serves two main

purposes. Firstly, it acts as a filter that removes, from the irradiance spectrum produced by the pre-heating device, all radiation at a diagnostic wavelength, which in this embodiment is **1450** nm. In other words, the water-cooled window effectively renders the radiation spectrum produced by the pre-heating device (or any reflections thereof by the workpiece) invisible to all measuring devices in the system **100** that detect radiation at the diagnostic wavelength. Secondly, it absorbs infrared radiation thermally emitted by the wafer **120** as it becomes hot, thereby preventing such radiation from reflecting back to the wafer **120** and causing undesirable (and non-uniform) heating thereof at inopportune times, such as during a cooling stage, for example. (In practice, it has been found that a small amount (e.g. 3%) of the radiation thermally emitted by the wafer **120** at the **1450** nm diagnostic wavelength may be inadvertently reflected back to the wafer by the top quartz pane of the window, rather than passing through the top pane to be absorbed in the water-cooling channel defined between the quartz panes. This latter effect is referred to as chamber return, and may be taken into account in the calibration of the various measuring devices employed in the system **100**, if desired.)

In the present embodiment, the system **100** further includes a plurality of additional measurement devices, including a diagnostic illumination source **160**, and radiation detectors. More particularly, in this embodiment the radiation detectors include the second measurement device **116**, which in this embodiment includes a fast radiometer **164**. Similarly, the radiation detectors further include another measurement device **117**, which in this embodiment includes an imaging device **162**. Generally, in this embodiment the diagnostic illumination source **160** and the imaging device **162** are used to capture images of the second surface **118** of the workpiece **106** and of the reference piece **142** to determine the hemispherical reflectivity of the workpiece, and the fast radiometer **164** is used to measure thermal emission from the workpiece. The thermal emission and hemispherical reflectivity measurements may be combined to yield the temperature of the second surface **118** of the workpiece, as discussed in greater detail below.

In this embodiment, the reference piece **142** is tilted slightly relative to the plane of the workpiece **106**, and the diagnostic illumination source **160** and the imaging device **162** are angled so that both the reference piece and the workpiece reflect incident radiation from the diagnostic illumination source toward the imaging device **162** at an angle of maximum reflective intensity. If desired, the diagnostic illumination source **160**, the imaging device **162** and the radiometer **164** may be disposed at equal angles relative to a central region **170** of the wafer **120**. Such a configuration may reduce measurement errors in embodiments such as the present embodiment, where the second surface **118** of the workpiece **106** is not isotropically diffuse (Lambertian). Alternatively, however, the devices **160**, **162** and **164** may be disposed at different angles, at the expense of increased measurement errors in any embodiment where the workpiece is not radially symmetric about the normal of the workpiece at its center. In the present embodiment, the devices **160**, **162** and **164** are all positioned so as to bypass the water-cooled window **156**, so that the water-cooled window **156** does not filter illuminating radiation produced by the diagnostic illumination source **160**, nor does it filter radiation received by the imaging device **162** or the fast radiometer **164**.

In the present embodiment, the system **100** further includes an irradiance system **180** operable to expose the first surface **104** of the workpiece **106** to an irradiance flash incident thereon. More particularly, in this embodiment the irradiance system **180** includes a flash lamp **182** and a reflector system **184**, positioned immediately above the upper wall **132** of the chamber **130**. Alternatively, a plurality of flash lamps may be employed if desired, or other suitable types of irradiance devices may be substituted for the flash lamp. In this embodiment, the upper wall **132** includes a water-cooled window **186**, similar to the water-cooled window **156** discussed above, which acts as a filter for removing radiation at the diagnostic wavelength of **1450** nm from the irradiance spectrum produced by the flash lamp **182**, and for absorbing thermal emission from the wafer at this wavelength. In the present embodiment, the irradiance system **180** further includes a power control system **188** for supplying electrical power to the flash lamp **182** to produce the irradiance flash.

In this embodiment, prior to the insertion of the wafer **120** into the chamber **130**, the device side **122** of the wafer is subjected to an ion implantation process, which introduces impurity atoms or dopants into a surface region of the device side of the wafer. The ion implantation process damages the crystal lattice structure of the surface region of the wafer, and leaves the implanted dopant atoms in interstitial sites where they are electrically inactive. In order to move the dopant atoms into substitutional sites in the lattice to render them electrically active, and to repair the damage to the crystal lattice structure that occurs during ion implantation, it is necessary to anneal the surface region of the device side of the wafer by heating it to a high temperature.

In the present embodiment, such annealing is carried out according to methods such as those disclosed in the aforementioned commonly-owned PCT publication numbers WO **02/47143** and WO **02/47123**. For example, a first stage of the annealing method may include pre-heating the wafer to an intermediate temperature, at a rate that is slower than a thermal conduction time through the wafer, so that the entire wafer is heated relatively uniformly to the intermediate temperature. In this embodiment, this pre-heating stage is achieved by irradiating the back-side or substrate side **124** of the wafer with the arc lamp **152**, to heat the wafer at a ramp rate such as **100** °C per second to **400** °C per second, to an intermediate temperature such as **500** °C to **1100** °C, for example. Following the pre-heating stage, the top-side or device side **122** of the wafer is rapidly heated to a substantially higher annealing temperature, at a rate much faster than the thermal conduction time through the wafer, so that only the top-side surface region of the wafer is heated to the final annealing temperature, while the bulk of the wafer remains close to the relatively cooler intermediate temperature. In this embodiment, this second stage is achieved by exposing the top-side surface to a high-power flash from the irradiance system **180**, for a relatively short duration, on the order of one millisecond, for example. The cooler bulk of the wafer then acts as a heat sink to facilitate rapid cooling of the top-side surface.

In order to ensure adequate thermal processing of such wafers, and to achieve consistent thermal processing of similar wafers successively processed in the chamber **130**, it is desirable to monitor the device side temperature during the second stage, i.e., during the rapid irradiance flash, in real-time, as discussed in greater detail herein. In some cases, if physical parameters of the irradiance system **180** tend to vary over time, consistency of thermal processing may be enhanced by using such real-time device side temperature values to control the power of the irradiance flash while it is occurring. Thus, in the present embodiment, the at least one processor circuit is configured to control a power of the irradiance flash in response to the present temperature of the first surface **104** of the workpiece **106**, as discussed in greater detail below.

Substrate Side Pre-Heating Device

In the present embodiment, the arc lamp **152** is a **500** kW double water wall argon plasma arc lamp available from Vortek Industries Ltd. of Vancouver, British Columbia, Canada. An example of such an arc lamp is disclosed in commonly-owned Patent Cooperation Treaty application publication No. **WO 01/54166**, which is incorporated herein by reference. Such arc lamps provide numerous advantages for semiconductor annealing as compared to tungsten filament lamp sources, as discussed in the above-mentioned PCT publication. For larger temperature increases, multiple arc lamps may be substituted for the single arc lamp **152**. Alternatively, however, other types of pre-heating devices, including flash lamps and even tungsten filament lamp sources or arrays of such lamp sources, for example, may be substituted.

Diagnostic Illumination Source

In this embodiment, the diagnostic illumination source **160** is operable to produce a diagnostic flash at the diagnostic wavelength of **1450** nm for illuminating the wafer **120** and the reference piece **142**. To achieve this, the diagnostic illumination source **160** includes a short-arc xenon arc lamp **190** having a pulsed discharge power supply

unit (not shown) for causing the arc lamp **190** to function as a flash lamp, and an incoherent optical fiber bundle **192**, which bypasses the water-cooled window **156** of the lower wall **134** of the chamber **130**. Radiation from the arc lamp **190** is channeled through the incoherent optical fiber bundle **192**, bypassing the filter water-cooled window **156**, thus allowing radiation at the diagnostic wavelength to illuminate the substrate side **124** of the wafer **120** and the reference piece **142** with a diagnostic flash at the diagnostic wavelength, whenever required for measurement purposes. Alternatively, however, any other suitable configuration for producing such a diagnostic flash may be substituted. For example, a continuous illumination source, such as one or more tungsten filament lamps for example, may be used in conjunction with a mechanical shutter (not shown) operable to rapidly open and shut to illuminate the wafer and reference piece. If so, the shutter is preferably radiation-absorbing and cooled. As a further illustrative example, one or more photodiodes or laser diodes emitting at the diagnostic wavelength of **1450** nm may be substituted for the arc lamp **190**.

Imaging Device

Generally, in this embodiment, the measurement device **117**, or more particularly the imaging device **162**, is in communication with the at least one processor circuit, which is configured to cooperate with the imaging device to measure the hemispherical reflectivity of the second surface **118** of the workpiece **106**. More particularly, in this embodiment the imaging device **162** acts as a radiation detector configured to receive radiation reflected by the second surface **118**, the detector being positioned sufficiently far away from the second surface to avoid obstructing the second surface from fields of view of other devices of the system, such as the fast radiometer **164** and the diagnostic illumination source **160**, for example. To achieve this, in the present embodiment the imaging device is positioned a distance from a center of the second surface **118** at least as great as one-half of the largest dimension of the workpiece **106**. The imaging device is configured to measure a directional

reflectivity of the second surface, and the at least one processor circuit is configured to apply a scattering correction to the directional reflectivity to obtain the hemispherical reflectivity, as discussed in greater detail below. Thus, the imaging device **162** is advantageous as compared to conventional devices for measuring hemispherical reflectivity, which typically must be placed very close to the measured object, such as integrating hemispheres, for example.

In this embodiment, the imaging device **162** includes an infrared camera operable to produce images of both the workpiece **106** and the reference piece **142**, which are both within the field of view of the imaging device **162**. In the present embodiment, the infrared camera includes a diode array, or more particularly, a photodiode focal plane array. More particularly still, in this embodiment the infrared camera includes a **320x256** pixel Indium-Gallium-Arsenide (InGaAs) photodiode array, which has a **12**-bit sensitivity. The camera also includes focussing optics (not shown), and further includes a narrow-band filter centered about **1450** nm, so that the camera is sensitive only to the diagnostic wavelength of **1450** nm and a very narrow bandwidth (e.g. ± **15** nm) centered thereabout. Thus, in this embodiment the imaging device **162** is configured to measure the directional reflectivity of the second surface **118** of the workpiece in an illumination wavelength band in which a heating irradiance spectrum incident upon the second surface has negligible intensity. In this regard, it will be recalled that the system **100** effectively includes a filtering device configured to remove the illumination wavelength band from the heating irradiance spectrum. (More particularly, in this embodiment the filtering device includes the water-cooled window **156** interposed between the second surface **118** and the source of the heating irradiance spectrum, i.e., the arc lamp **152**, as the water-cooled window blocks the entire diagnostic wavelength band of **1450±15** nm to which the imaging device **162** is sensitive). Alternatively, other imaging devices, such as other two- or one-dimensional diode arrays, or charge-coupled devices (CCDs) for example, may be substituted.

Referring to Figures **1** and **2**, in this embodiment the imaging device **162** is in communication with a digital frame grabber card **200** of the RTP System Computer (RSC) **112**, for communicating digital data representing images of the workpiece **106** and the reference piece **142** to the processor circuit **110** of the RSC **112**. Alternatively, if desired, the imaging device may be placed in communication with a separate processor circuit remote from the RSC **112** and in communication therewith.

If desired, in addition to using such digital image data to determine the hemispherical reflectivity of the workpiece **106** in order to measure its temperature, such image data may also be used to produce real-time two-dimensional temperature maps of the second surface **118** of the workpiece **106**. These temperature maps are useful for determining the uniformity of the heating of the workpiece during the entire thermal process. Spatially resolved temperature maps are discussed in greater detail in the aforementioned commonly-owned U.S. Patent No. **6,303,411**, for example.

In this embodiment, the imaging device **162** and the diagnostic illumination source **160** are also in communication with a synchronization module **202**.

Synchronization Module

Referring to Figures **1** and **2**, in this embodiment, the synchronization module **202** is used to synchronize the imaging device **162** with the diagnostic illumination source **160**, to enable the imaging device **162** to produce images of the workpiece **106** and the reference piece **142** when illuminated by the diagnostic flash (as well as prior to and/or following the diagnostic flash, if desired).

To achieve this, the synchronization module **202** receives a video frame sync signal from the imaging device **162**, in response to which it generates a pulse signal with an adjustable delay, to activate the diagnostic illumination source **160** at the desired time. If desired, different types of video frame sync signals can be selected, such as

composite analog video, standard TTL video and LVDS differential digital video, for example.

To generate the adjustably delayed pulse signal to activate the diagnostic illumination source **160** in response to the video frame sync signal from the imaging device **162**, the synchronization module **202** includes an internal clock **204**, which in this embodiment is a **48** MHz clock, and is capable of generating "on" and "off" delay signals with adjustable delays ranging from **0** to **99,999** microseconds with a **1**-microsecond resolution, and delay accuracy better than **40** nanoseconds. In this embodiment, the synchronization module **202** generates an "on" pulse signal to activate the diagnostic illumination source **160** immediately prior to the commencement of the integration period of the imaging device **162**, to ensure that the imaging device **162** captures reflected radiation from the workpiece and reference piece when the diagnostic illumination source is illuminating the workpiece and reference piece at its peak intensity, thereby maximizing the signal-to-noise ratio of the resulting digital reflectance images.

<u>RTP System Computer (RSC)</u>

Referring to Figures **1** and **2**, the RTP System Computer (RSC) is shown in greater detail at **112** in Figure **2**. In this embodiment, the RSC includes the processor circuit **110**, which in the present embodiment includes a microprocessor **210**. More generally, however, in this specification, the term "processor circuit" is intended to broadly encompass any type of device or combination of devices capable of performing the functions described herein, including (without limitation) other types of microprocessors, microcontrollers, other integrated circuits, other types of circuits or combinations of circuits, logic gates or gate arrays, or programmable devices of any sort, for example, either alone or in combination with other such devices located at the same location or remotely from each other, for example. Additional types of processor circuits will be apparent to those ordinarily skilled in the art upon review of

this specification, and substitution of any such other types of processor circuits is considered not to depart from the scope of the present invention as defined by the claims appended hereto.

In the present embodiment, the microprocessor **210** is in communication with a storage device **220**, which in this embodiment includes a hard disk drive. The storage device **220** is used to store a plurality of routines that configure or program the microprocessor **210** to perform various functions described herein, including a standard ratio routine **222**, a hemispherical reflectivity routine **224**, a temperature monitoring and control routine **226**, and a network synchronization algorithm **228**. Generally, the network synchronization algorithm **228** is employed by the processor circuit **110** to regulate network communications between the RSC **112** and various other devices of the system **100**, to ensure that non-deterministic latency is less than **50** μs. The remaining routines are discussed in greater detail below.

In this embodiment, the storage device **220** is also used to store various types of data received or used by the microprocessor **210**. More particularly, in the present embodiment the storage device **220** includes an image frames store **242** for storing digital data representing images of the workpiece **106** and the reference piece **142** received from the imaging device **162**, a temperature history store **244** for storing workpiece temperature values received from the fast radiometer **164**, and a look-up table store **246** for storing a look-up table used by the microprocessor **210** to identify a temperature of the first surface **104** of the workpiece **106**, in response to a temperature of the second surface **118** unequal to the temperature of the first surface, and the temperature history of the workpiece.

In the present embodiment, the microprocessor **210** is also in communication with a memory device **260**, which in this embodiment includes a random access memory (RAM). The memory device **260** is used by the microprocessor **210** for storage of values representing various physical properties identified or used by the

microprocessor in the execution of the various routines stored in the storage device **220**. More particularly, in this embodiment such routines direct the microprocessor **210** to define, in the RAM, a plurality of registers, including a standard reflectivity register **264**, a standard ratio register **266**, a workpiece ratio register **270**, a directional reflectivity register **272**, a scattering values register **274**, a scattering correction register **276**, a hemispherical reflectivity register **278**, a substrate temperature register **280**, a ramp rate register **282**, and a device side temperature register **284**, discussed in greater detail below.

In this embodiment, the microprocessor **210** is in communication with the digital frame grabber card **200**, for receiving digital data representing infrared images of the workpiece **106** and the reference piece **142** produced by the imaging device **162**.

The microprocessor **210** of the present embodiment is in further communication with an input/output (I/O) interface **290**, for communicating with various devices of the system **100** shown in Figure **1**, including the fast radiometer **164**, the measurement device **102**, the irradiance system **180**, the pre-heating device **150**, a user-input device (not shown) such as a keyboard and/or a mouse, for example, and the synchronization module **202** for controlling the diagnostic illumination source **160** and the imaging device **162**. In this embodiment, the I/O interface **290** includes an optical-electrical converter, for communicating with at least some of these devices (such as the fast radiometer **164** and the measurement device **102**, for example) via a fiber optic network **292**. In this regard, it will be appreciated that such optical communications avoid difficulties posed by electromagnetic interference and electrical noise resulting from large electrical currents and sudden electrical discharges required by the pre-heating device **150** and the irradiance system **180**.

<u>Fast Radiometer</u>

Referring to Figures **1** and **3**, the measurement device **116**, or more particularly, the fast radiometer, is shown generally at **164** in Figure **3**. Generally, in this embodiment,

the fast radiometer **164** receives electromagnetic radiation thermally emitted by the second surface **118** of the workpiece **106** at the diagnostic wavelength of **1450** nm, and produces corresponding emissivity-compensated temperature values representing the temperature of the second surface of the workpiece.

To achieve this, in the present embodiment the fast radiometer **164** includes a narrow-band filter **302** centered about the diagnostic wavelength of **1450** nm, for blocking wavelengths other than the diagnostic wavelength. The fast radiometer further includes an optical stack **304**, for focussing electromagnetic radiation emitted from the central region **170** of the second surface **118** of the workpiece onto an active element of a photodiode **306**, which in this embodiment includes a high-speed, low-noise, InGaAs PIN photodiode. In this embodiment, the central region **170** includes an area of approximately **2** cm in diameter at the center of the substrate side **124** of the wafer **120**.

The photodiode **306** is in communication with an amplifier **308**, which in this embodiment includes a differential transimpedance amplifier, having a **3** dB electrical bandwidth of approximately **2.5** kHz. The amplifier **308** conditions and amplifies the output signal from the photodiode, and supplies the amplified signal to an analog-to-digital (A/D) converter **310**. In the present embodiment, the A/D converter **310** produces **20**-bit samples of the amplified photodiode signal, at an over-sampling rate of **25** kHz.

The A/D converter **310** is in communication with the processor circuit **114** of the fast radiometer **164**. The processor circuit **114** is in communication with first and second storage devices, which in this embodiment include a program memory **314** and a working memory **316**. The program memory stores instruction codes or routines which configure the processor circuit **114** to perform various functions, including a substrate temperature routine **318**, which directs the processor circuit **114** to identify the temperature of the substrate side **124** of the wafer **120**, as discussed in greater

detail below. The substrate temperature routine **318** directs the processor circuit **114** to define, in the working memory **316**, a plurality of registers, including a hemispherical reflectivity register **320** and a substrate temperature register **322**. The program memory **314** may include any suitable type of memory device, but is preferably a non-volatile memory, such as a ROM, an EPROM, an EEPROM or a FLASH memory, for example. Similarly, the working memory **316** may include any suitable type of memory device, such as a RAM, for example.

The processor circuit **114** is in communication with an input/output (I/O) interface **330**, for communication with the processor circuit **110** of the RSC **112** shown in Figure **1**. In this embodiment, the I/O interface **330** includes an optical-electrical converter, for communicating with the RSC via the fiber-optic network **292**. As discussed below, in this embodiment the fast radiometer **164** effectively measures the temperature of the substrate side **124** of the wafer **120** every millisecond, and supplies updated substrate temperature values to the RSC at a rate of **1** kHz. The fast radiometer **164** also periodically receives updated hemispherical reflectivity values from the RSC, which it combines with substrate side thermal emission intensity values to produce the substrate temperature values.

<u>Device Side Irradiance System</u>

Referring back to Figure **1**, generally, the irradiance system **180** is operable to irradiate the device side **122** of the wafer **120**. The measurement device **102** and the at least one processor circuit are configured to measure the present intensity and identify the present temperature of the device side **122**, while the device side is being irradiated by the irradiance system **180**.

In this embodiment, the irradiance system **180** includes the flash lamp **182** (or a plurality of such flash lamps if desired) and the reflector system **184** shown in Figure **1**. More particularly in this embodiment the flash lamp **182** includes a high intensity

arc lamp similar to that disclosed in the aforementioned commonly-owned Patent Cooperation Treaty application publication number WO 01/54166.

In the present embodiment, the irradiance system 180 is operable to expose the device side 122 to an irradiance flash having a duration less than a thermal conduction time of the wafer 120. In the present embodiment, the thermal conduction time of the wafer is on the order of 10 to 15 ms. Accordingly, in the present embodiment, the irradiance system 180 is operable to produce the irradiance flash to have a duration on the order of 10 milliseconds or less. More particularly, in this embodiment the irradiance system is operable to produce the irradiance flash to have a duration on the order of 1 millisecond.

To achieve this, in the present embodiment, the irradiance system 180 further includes the power control system 188 shown in Figure 1. More particularly, in this embodiment the power control system 188 acts as a power supply system, and includes a pulsed discharge unit that may be pre-charged then abruptly discharged in order to supply a "spike" of input power to the flash lamp 182 to produce the desired irradiance flash. More particularly still, in the present embodiment the pulsed discharge unit includes a power supply model number VT-20 pulsed discharge unit manufactured by Rapp OptoElectronic of Hamburg, Germany, operable to produce pulses of up to 60 kJ within discharge times ranging from approximately 0.5 to 5 ms, such as a one-millisecond discharge time, for example. In response to such a discharge, the flash lamp 182 is operable to produce a heating flash of electromagnetic radiation with a power output of 4 - 6 MW ranging from 0.5 - 5 ms in duration. Alternatively, much larger power supplies, operable to discharge 300 kJ for example, may be substituted. More generally, other heating devices may be substituted for the irradiance system 180 if desired.

In this embodiment, the power control system **188** includes a power control circuit interposed between the pulsed discharge unit and the flash lamp **182**, for feedback control of the pulsed discharge, as discussed below.

Ultra-Fast Radiometer

Referring to Figures **1** and **4**, the measurement device is shown generally at **102** in Figure **4**. In this embodiment, the measurement device **102** includes an ultra-fast radiometer **400**. Generally, the ultra-fast radiometer acts as a measurement device configured to measure a present intensity of radiation thermally emitted from the first surface **104** of the workpiece **106**. The ultra-fast radiometer also includes a processor circuit in communication with the measurement device, configured to identify a present temperature of the first surface **104**, in response to the present intensity and at least one previous thermal property of the first surface **104**, as discussed in greater detail herein. More particularly, in this embodiment the ultra-fast radiometer **400** is configured to cooperate with the at least one processor circuit to identify the temperature of the device side **122** of the wafer **120**, during the rapid irradiance flash produced by the irradiance system **180**. Such a flash may have a duration on the order of one millisecond, for example, and may raise the device side temperature by hundreds of degrees Celsius, for example. Accordingly, the ultra-fast radiometer **400** is designed to have a wide dynamic range and ultra-fast time response.

Referring to Figures **1**, **3** and **4**, in this embodiment, the ultra-fast radiometer **400** is similar in some (but not all) respects to the fast radiometer **164** shown in Figure **3**. Thus, the ultra-fast radiometer **400** includes a **1450** nm narrow-band filter **402**, an optical stack **404** and a high-speed InGaAs PIN photodiode **406**, which in this embodiment are similar to the corresponding components **302**, **304** and **306** of the fast radiometer. However, in this embodiment, the photodiode **406** includes an integrated thermo-electric cooler **408**, for controlling the temperature of the photodiode **406** to within **20** milliKelvins.

The output signal from the photodiode **406** is supplied to an amplifier **410**. In this embodiment, the amplifier **410** includes a very low noise, high-speed, differential transimpedance amplifier, having a **3** dB electrical bandwidth of **500** kHz. The amplifier **410** conditions and amplifies the photodiode output signal, and supplies the amplified signal to an analog-to-digital (A/D) converter **412**. The A/D converter **412** produces **16**-bit samples of the amplified photodiode signal, at a sampling rate of **1** MHz.

The A/D converter **412** is in communication with the processor circuit **108** of the ultra-fast radiometer **400**. The processor circuit **108** is in communication with first and second storage devices, which in this embodiment include a program memory **416** and a memory device **418**. The program memory **416** stores routines that configure the processor circuit **108** to perform various functions, including a real-time device side temperature routine **420**, and a dynamic calibration routine **422**. The real-time device side temperature routine **420** directs the processor circuit **108** to define, in the memory device **418**, a plurality of registers and/or stores, including a device side thermal emission intensity store **430**, an initial device side temperature register **432**, an initial device-side thermal intensity register **434**, a device side temperature register **436**, and a device side temperature values store **438**.

In this embodiment, the processor circuit **108** is in communication with an internal reference device **450**. In this embodiment, the internal reference device is thermally controlled and highly stable, and is used to produce calibration and reference signals. The dynamic calibration routine **422** directs the processor circuit **108** to adjust the **16**-bit samples received from the A/D converter **412** in response to the calibration and reference signals received from the internal reference device **450**, in order to dynamically compensate for any unpredictable drift that may occur in the various electronic components of the ultra-fast radiometer.

In the present embodiment, the processor circuit **108** is in further communication with an input/output (I/O) interface **460**, for communication with the processor circuit **110** of the RSC **112**, and with other components of the system **100** shown in Figure **1**. In particular, in this embodiment the processor circuit **108** is in direct communication with the power control system **188** of the irradiance system **180**, to enable the processor circuit **108** to control the power of the irradiance flash produced by the irradiance system, in response to the real-time device side temperature values obtained by the processor circuit **108** during the course of the flash. In this embodiment, the I/O interface **460** includes an optical-electrical converter, to enable such communications signals to be transmitted and received over the fiber optic network **292**, thereby avoiding deleterious effects of electromagnetic interference and electrical noise, which may be significant in the temporal vicinity of the flash.

In this embodiment, the ultra-fast radiometer **400** further includes shielding **470**, to reduce the influence of such interference on the various internal components of the ultra-fast radiometer.

Referring back to Figure **1**, in this embodiment, the measurement device **102**, or more particularly the ultra-fast radiometer **400**, is configured to measure the present intensity of thermal emission from the first surface **104** of the workpiece **106**, in a wavelength band in which an irradiance spectrum incident upon the first surface has negligible intensity. To achieve this, in this embodiment, the system **100** effectively includes a filtering device configured to remove the wavelength band from the irradiance spectrum incident upon the first surface. More particularly, in this embodiment the filtering device includes the water-cooled window **186** interposed between the first surface **104** and a source of the irradiance spectrum, which in this embodiment is the irradiance system **180**. In this regard, it will be recalled that the water-cooled window **186** serves to transmit most of the radiation produced by the flash lamp **182** to the device side **122** of the wafer **120** to heat the device side, while at the same time absorbing radiation at the diagnostic wavelength of **1450** nm.

Conversely, due to the effects of the **1450** nm narrow-band filter **402**, the ultra-fast radiometer is responsive only to radiation in the immediate vicinity of **1450** nm. Therefore, the ultra-fast radiometer detects only thermal emissions from the device side **122**, and does not detect any radiation produced by the irradiance system and reflected by the device side. The water-cooled window **186** also serves to absorb most of the radiation at wavelengths thermally emitted by the device side **122** (typically **1400** nm and longer), thereby preventing such wavelengths from being reflected back to the wafer which would tend to cause undesirable and non-uniform heating of the device side at inopportune times when cooling is desired. (The ultra-fast radiometer may, however, detect a small amount of "chamber return", i.e., a small percentage of the radiation thermally emitted by the device side at the diagnostic wavelength may be reflected by the lower quartz pane of the window **186** back to the device side, which may re-reflect a small portion of such reflected thermal emissions to the radiometer. Chamber return may be taken into account within the execution of the dynamic calibration routine **422**, if desired.)

Operation

Standard Ratio Routine:

Referring to Figures **1**, **2** and **5**, the standard ratio routine is shown at **222** in Figure **5**. Generally, the standard ratio routine **222** configures the processor circuit **110** of the RSC **112** to calculate a value $RATIO_{STD}$, which is subsequently used by the processor circuit **110** in the course of the hemispherical reflectivity routine **224** to identify the hemispherical reflectivity of the substrate side **124** of the wafer **120**.

Prior to execution of the standard ratio routine, the wafer **120** is removed from the chamber **130**, and is replaced with a standard having a known reflectivity R_{STD}. Thus, for this initial measurement, the workpiece **106** includes a standard rather than a semiconductor wafer. In this embodiment, the standard is an aluminum wafer, however, any suitable standard having a known reflectivity may be substituted. Once

the standard has been placed in the chamber **130**, the standard ratio routine may be executed.

The standard ratio routine **222** includes various blocks of instruction codes which configure the processor circuit **110** to identify and store the desired value $RATIO_{STD}$. The standard ratio routine **222** begins with a first block **500** of codes, which directs the processor circuit **110** to effectively obtain an illuminated image of the standard and of the reference piece **142**. To achieve this, block **500** directs the processor circuit **110** to signal the synchronization module **202** shown in Figure **2**, in response to which the synchronization module receives the video sync signal from the imaging device **162** as described above. The synchronization module generates an electrical pulse signal to activate the diagnostic illumination source **160** immediately prior to the commencement of the integration period of the imaging device **162**, so that the imaging device captures an image of the workpiece **106** (in this case the standard) and the reference piece **142** while these latter objects are being illuminated by the diagnostic illumination flash with maximum intensity. The imaging device **162** transmits signals representing the captured image of the standard and of the reference piece to the digital frame grabber card **200**. The processor circuit **110** receives data from the frame grabber card representing the captured image, and stores the received data in the image frames store **242** in the storage device **220**.

Block **510** then directs the processor circuit **110** to calculate the value $RATIO_{STD}$. In this regard, it will be appreciated that if the intensity of the diagnostic flash incident upon the reference piece is I_0, then the intensity of the diagnostic flash incident upon the workpiece **106** is αI_0, where α is a constant determined by the geometry of the system **100**. Thus, the reference piece **142** reflects the diagnostic flash with an intensity $I_0 R_{REF}$, where R_{REF} is the reflectivity of the reference piece, and likewise, the workpiece **106**, which in this case is the standard, reflects the diagnostic flash with intensity $\alpha I_0 R_{STD}$. The data values that were stored in the image frames store **242** at block **500** above, produced by the imaging device **162**, or more particularly, by

individual photodiodes of the InGaAs photodiode array corresponding to the central region **170** of the workpiece **106** and by photodiodes corresponding to the reference piece **142** (or alternatively, by corresponding pixels if a CCD is substituted for the photodiode array), are used to calculate and store a ratio of the intensity reflected by the workpiece (in this case, the standard) to the intensity reflected by the reference piece, namely, $RATIO_{STD} = \alpha I_0 R_{STD}/I_0 R_{REF} = \alpha R_{STD}/R_{REF}$. Block **510** then directs the processor circuit **110** to store the resulting value $RATIO_{STD}$ in the standard ratio register **266** in the memory device **260**. The standard ratio routine is then ended.

The foregoing calculation of $Ratio_{STD}$ is calculated once, and typically does not need to be re-calculated for a given set of thermal cycles to be applied to similar wafers, unless a physical parameter of the system **100** changes (e.g., dirt on an illumination source). To determine whether or not $Ratio_{STD}$ should be recalculated, a "calibration wafer" or "diagnostic wafer" (for example, a semiconductor wafer having no devices and uniform dopant concentration) may be periodically thermally cycled in the system **100**, and resulting dopant activation may be measured (for example, by measuring sheet resistance of the wafer). Alternatively, other factors may suggest a desire for recalculation of $Ratio_{STD}$, such as a movement of the image of the wafer, or drastic changes in temperature measurements in one cycle as compared to previous cycles, for example.

Temperature Monitoring and Control Routine

The remaining routines employ at least some information derived directly or indirectly from wafer reflectivity measurements. As the wafer **120** is not sufficiently opaque to the **1450** nm diagnostic wavelength at temperatures below about **700** °C for such reflectivity measurements to be reliably accurate for many purposes, the remaining routines are described only in the context of a thermal cycle in progress, where the wafer has reached or exceeded a threshold temperature at which it is sufficiently opaque for such measurements to be accurately made at the diagnostic

wavelength. Alternatively, if desired, wafer reflectivity measurements may be obtained at shorter wavelengths, or may be predicted for the purpose of low-temperature measurements, if desired.

Referring to Figures **1**, **2** and **6**, the temperature monitoring and control routine is shown at **226** in Figure **6**. Generally, the temperature monitoring and control routine **226** configures the processor circuit **110** of the RSC **112** to control the pre-heating device **150** to irradiate the substrate side **124** of the wafer **120**, to pre-heat the wafer to a desired intermediate temperature at a ramp rate that is slow compared to a thermal conduction time of the wafer (as an arbitrary, illustrative example, such a ramp cycle may heat the wafer from room temperature to an intermediate temperature of **800** °C at a ramp rate of **250** °C/second). When the intermediate temperature is reached, the temperature monitoring and control routine directs the processor circuit to control the irradiance system **180** to initiate a flash cycle, to heat the device side **122** of the wafer **120** to a desired annealing temperature, at a rate much faster than the thermal conduction time of the wafer (as a further arbitrary illustrative example, the device side may be exposed to a one-millisecond flash to heat the device side to a temperature of **1300** °C, while the bulk of the wafer remains close to the intermediate temperature). Once the flash cycle has been initiated, the remainder of the flash cycle is controlled directly by the ultra-fast radiometer **400** under the direction of the real-time device side temperature routine **420**.

The temperature monitoring and control routine **226** begins with a first block **600** of codes, which directs the processor circuit **110** to control the pre-heating device **150**, or more particularly the arc lamp **152**, to begin pre-heating the workpiece **106** at a desired ramp rate. Typically, for a silicon semiconductor wafer, the desired ramp rate is in the range of **100** °C/second to **400** °C/second, although other ramp rates outside this range may be substituted if desired. In this embodiment, due to the fact that silicon is not opaque to **1450** nm radiation when it is below about **700** °C, the pre-heating cycle is initially commenced as an open-loop temperature cycle, based on

predicted wafer temperatures that are expected to result from supplying predetermined amounts of energy to the arc lamp **152**.

Block **602** then directs the processor circuit **110** to determine whether the predicted temperature of the workpiece **106** has reached a pre-defined threshold temperature. In this embodiment, where the workpiece is the semiconductor wafer **120**, the pre-defined temperature is approximately **600** °C, above which the wafer, although not yet completely opaque to the **1450** nm diagnostic wavelength, is sufficiently opaque to provide adequate signals for use by the temperature measurement and control routine. (As the wafer temperature increases beyond **700** °C, it becomes completely opaque to the diagnostic wavelength, thereby improving the accuracy of the system.)

If at block **602** it is predicted that the threshold temperature has been achieved, block **604** directs the processor circuit **110** to commence execution of the hemispherical reflectivity routine **224** (discussed in greater detail below in connection with Figure **7**) to periodically identify the hemispherical reflectivity of the wafer, which in turn can be used by the fast radiometer **164** to produce emissivity-compensated temperature measurements of the wafer.

Block **606** then directs the processor circuit **110** to begin continuously receiving and storing temperature values from the fast radiometer **164**, representing successive values of the temperature of the second surface **118** of the workpiece **106** (in this embodiment the substrate side **124** of the wafer **120**) at successive respective times. Each such temperature value is produced by the processor circuit **114** of the fast radiometer **164**, as discussed in greater detail below in connection with Figure **8**. Block **606** directs the processor circuit **110** to store each such received substrate temperature value, along with the current time, as a data pair ($T_{SUBSTRATE}$, t), in the temperature history store **244**, to effectively generate a temperature history record of the wafer. Although block **606** is shown in Figure **6** as a single block of instruction codes for ease of illustration, in this embodiment block **606** continues to direct the

processor circuit to receive and store such substrate temperature values throughout the course of the pre-heating cycle, the subsequent flash cycle, and the radiative cooling stage thereafter.

Block **608** then directs the processor circuit **110** to switch to a closed-loop pre-heating cycle. More particularly, block **608** directs the processor circuit **110** to begin comparing the substrate temperature values received from the fast radiometer to the predicted or desired substrate temperatures for each corresponding time-point in the thermal cycle, and to increase or decrease the power supplied to the arc lamp **152** so as to minimize or eliminate any deviations of the actual (measured) substrate temperature from the desired or predicted temperature. If desired, the closed-loop pre-heating cycle may include spatially resolved irradiance control, such as any of the methods disclosed in the aforementioned commonly-owned U.S. Patent No. **6,303,411**, for example.

While block **606** and **608** continue to execute, block **610** directs the processor circuit **110** to compare the most recently received substrate temperature value to a pre-defined intermediate temperature at which the flash cycle is to be commenced.

If it is determined at block **610** that the intermediate temperature has been achieved, block **612** directs the processor circuit **110** to store the most recently received substrate temperature value $T_{DEVICE}(t_0)$ in the substrate temperature register **280** (if desired, the corresponding time value t_0 may also be stored). Block **612** then directs the processor circuit **110** to identify a thermal property of the first surface **104** of the workpiece **106**, or more particularly, a temperature of the device side **122** of the wafer **120** immediately preceding commencement of the irradiance flash. In this embodiment, the temperature of the first surface **104** is identified in response to a temperature of the second surface **118** of the workpiece unequal to the temperature of the first surface **104**. More particularly, the temperature of the first surface **104** is identified in response to the temperature of the second surface **118** and the

temperature history of the workpiece **106**. More particularly still, block **612** directs the processor circuit **110** to use the temperature of the second surface **118** and the temperature history to address a look-up table record in the look-up table store **246**, to identify the temperature of the first surface **104**.

In this embodiment, the look-up table stored in the look-up table store **246** has been previously pre-calculated and stored, using a thermal modelling routine (not shown), which in this embodiment includes TAS Thermal Analysis System software, available from Harvard Thermal, Inc. of Harvard, Massachusetts, USA. To produce the look-up table, the TAS routine is provided with input data, which in this embodiment includes thermal properties (e.g., heat conductivity, heat capacity, emissivity) and physical properties (e.g. thickness) of the workpiece **106**, and is also provided with an exemplary set of temperature history values $T_{History}$, the latter being provided as a set of temperature and time datapoints $[T_{Substrate}(t), t]$ as discussed above. In this embodiment, the emissivity value initially supplied to the TAS routine is first obtained empirically, by heating the workpiece and allowing it to cool, and measuring the temperature of the workpiece as it cools. The rate of cooling is analyzed with the TAS routine, and a parametric fit (with emissivity as a parameter) is performed to determine radiative energy loss as a function of temperature, from which the emissivity of the workpiece is obtained. Alternatively, the emissivity of the workpiece may be obtained or predicted in other ways, or may be known in advance. Once the emissivity of the workpiece is obtained, the emissivity is then supplied, along with the other input values (the thermal properties and thickness of the workpiece, and the exemplary temperature history values noted above), to the TAS routine.

In response to such input values, the execution of the TAS routine produces a value representing the final instantaneous device side temperature T_{Device} at the same point in time as the final substrate side temperature data point. The corresponding instantaneous substrate side temperature $T_{Substrate}$ is subtracted from the simultaneous

device side temperature T_{Device} to determine a temperature correction ΔT, which is typically negative and is typically on the order of fractions of a degree to several degrees Celsius (for example, if a typical wafer is heated to an intermediate temperature of **800** °C at a ramp rate of **150** °C/second, by irradiating only the substrate side of the wafer, the ΔT value would be approximately **–4.7** °, meaning the device side would be nearly **5** ° cooler than the substrate side at the time the substrate side reached the intermediate temperature).

This process is then repeated for a significant number of different permutations of exemplary temperature history input data corresponding to different respective model thermal cycles, to generate different respective ΔT values. For example, in the present embodiment, permutations of input data with ramp rates (corresponding to increase rates of $T_{Substrate}(t)$ in stored temperature history values) ranging from **50** °C/s to **400** °C/s, final instantaneous substrate temperatures $T_{Substrate}$ ranging from **600** °C to **1450** °C, and wafer thicknesses ranging from **0.5** to **1.0** mm, are used to produce the look-up table, so that a corresponding temperature correction ΔT may be quickly obtained for any permutation of values in such ranges. Alternatively, other ranges of input data may be substituted.

Thus, in the present embodiment the look-up table stored in the look-up table store **246** has four columns (not shown): a first column for average Ramp Rate, a second column for the final instantaneous substrate side temperature $T_{Substrate}(t_0)$ immediately before the heating flash, a third column for workpiece thickness, and a fourth column for the device side temperature correction ΔT that is to be added to the final instantaneous substrate side temperature $T_{Substrate}(t_0)$ to yield the corresponding simultaneous device side temperature $T_{DEVICE}(t_0)$. (Alternatively, if desired, a column may be provided for the corresponding simultaneous device side temperature itself, rather than a temperature correction to be added to the substrate side temperature to yield the device side temperature.)

To use the pre-calculated look-up table in operation, therefore, block **612** directs the processor circuit **110** to analyze the substrate temperature and time value pairs [$T_{Substrate}(t)$, t] stored in the temperature history store **244**, and to calculate an average ramp rate (for example, by setting the average ramp rate equal to the slope of a linear best-fit curve of a plot of $T_{Substrate}(t)$ versus t on the y and x axes, respectively), representing the average rate at which the substrate side **124** of the wafer was raised to the intermediate temperature. Block **612** directs the processor circuit to temporarily store the average ramp rate in the ramp rate register **282**. Block **612** then directs the processor circuit to use the average ramp rate stored in the ramp rate register **282**, the substrate temperature value $T_{SUBSTRATE}(t_0)$ stored in the substrate temperature register **280**, and the thickness of the workpiece, to address the look-up table, to locate a corresponding entry or record having matching values in the first three columns thereof. (The thickness of the workpiece may be a specified parameter of the temperature monitoring and control routine **226**, or alternatively, may be specified by a user of the system **100** and stored in a separate register, not shown, in the memory device **260**, if desired). Upon locating such a matching record, block **612** directs the processor circuit **110** to read the corresponding temperature correction value ΔT from the fourth column of the located record. Block **612** directs the processor circuit to add the located ΔT value (which in this embodiment is typically negative) to the final substrate side temperature $T_{SUBSTRATE}(t_0)$ stored in the substrate temperature register **280**, to yield the corresponding simultaneous instantaneous device side temperature $T_{DEVICE}(t_0)$. The processor circuit is directed to store this value in the device side temperature register **284**.

Block **614** then directs the processor circuit **110** to transmit the instantaneous device side temperature $T_{DEVICE}(t_0)$ to the ultra-fast radiometer **400**. Block **614** also directs the processor circuit **110** to shut down the arc lamp **152** to end the pre-heating cycle, and at the same time, signal the irradiance system **180** to begin producing the irradiance flash to rapidly heat the device side **122** of the wafer **120** to the desired annealing temperature.

(As an alternative, if desired, the processor circuit may be directed control the irradiance system **180** to begin supplying a low current to the flash lamp **182** a fraction of a second before the intermediate temperature is reached, to prepare the flash lamp for the flash. However, such an approach will tend to reduce the magnitude of the ΔT values stored in the look-up table as compared to single-side irradiance pre-heating, and accordingly, the look-up table values should be adjusted to accommodate this alternative approach.)

The temperature monitoring and control routine **226** is then effectively ended, with subsequent device side temperature monitoring and flash intensity being controlled by the ultra-fast radiometer **400** under the direction of the real-time device side temperature routine **420**, as discussed below. However, in this embodiment, the continuous receiving and storage of substrate temperature values by the processor circuit **110** under the direction of block **606** above is continued for a pre-defined time thereafter, to produce and store continuing substrate temperature values during and following the flash cycle, as the wafer cools.

<u>Hemispherical Reflectivity Routine</u>

Referring to Figures **1**, **2** and **7**, the hemispherical reflectivity routine is shown at **224** in Figure **7**. Generally, the hemispherical reflectivity routine **224** configures the processor circuit **110** of the RSC **112** to cooperate with the measurement device **117**, or more particularly with the diagnostic illumination source **160**, to measure the hemispherical reflectivity of the second surface **118** of the workpiece **106**. Such hemispherical reflectivity values are then effectively communicated to the fast radiometer **164**, which uses these values to produce emissivity-compensated temperature measurements of the substrate side **124** of the wafer **120**.

The initial steps of the hemispherical reflectivity routine are somewhat similar to those discussed above in connection with the standard ratio routine **222** shown in Figure **5**. However, prior to execution of the hemispherical reflectivity routine, the

standard discussed above in connection with the standard ratio routine is removed from the chamber **130**, and is replaced with the semiconductor wafer **120**. With the wafer in place, the temperature monitoring and control routine **226** shown in Figure **6** is executed, resulting in the execution of the hemispherical reflectivity routine commencing at block **604** above, once the wafer has reached a sufficiently high temperature to be opaque to radiation at the **1450** nm diagnostic wavelength.

In this embodiment, the hemispherical reflectivity routine **224** begins with a first block **700** of codes, which directs the processor circuit **110** to effectively obtain an image of the substrate side **124** of the wafer **120** and of the reference piece **142**, while the wafer and reference piece are being illuminated with the diagnostic illumination source **160**, in a manner similar to that discussed above in connection with block **500** of the standard ratio routine. However, as the wafer is now hot, in excess of about **700** °C, the image captured by the imaging device **162** during the diagnostic illumination flash will include not only reflected radiation produced by the diagnostic illumination source, but also radiation thermally emitted by the wafer and the reference piece. Accordingly, for the purpose of measuring the hemispherical reflectivity of the workpiece, it is desirable to be able to disregard the effect of such thermal emissions. This may be achieved in a number of ways. For example, the diagnostic illumination source may produce a sufficiently powerful diagnostic flash that thermal emissions from the workpiece are negligible in comparison to the reflected flash. In the present embodiment, however, block **700** directs the processor circuit to signal the synchronization module **202** to effectively obtain a set of three images of the workpiece and reference piece. The first image is captured immediately before a diagnostic illumination flash is commenced, the second image is captured while the diagnostic illumination flash is illuminating the wafer **120** and the reference piece **142** with maximum intensity, and the third image is captured immediately after the diagnostic illumination flash has ceased. Thus, the first image and the third image are effectively thermal emission intensity images, and the second image represents thermal emission intensity plus the intensity of the reflected diagnostic illumination

flash. Once a set of three such images has been received by the processor circuit **110** via the digital frame grabber card **200**, for each of the photodiodes in the photodiode array of the imaging device, the processor circuit is directed to calculate an average of the data values for that photodiode in the first and third images, which were captured while the diagnostic illumination source was off. This average value represents the approximate intensity of thermal radiation that the corresponding location of the wafer (or the reference piece, as the case may be) thermally emitted at the time the second image was captured. Therefore, this average value is subtracted from the intensity value for that photodiode in the second image, to yield a corrected reflectivity image of the wafer **120** and the reference piece **142** representing only the reflected intensity of the diagnostic illumination flash, without any thermal emission component. The corrected reflectivity image is then stored in the image frames store **242**.

Block **710** then directs the processor circuit **110** to calculate a ratio in a manner similar to that discussed in connection with block **510** of the standard ratio routine. In this regard, it will be recalled that the intensity of the diagnostic flash incident upon the reference piece is I_0, and therefore, the intensity of the diagnostic flash incident upon the workpiece **106** is αI_0, where α is the same constant referred to in connection with block **510**, and is determined by the geometry of the system **100**. Thus, the reference piece **142** reflects the diagnostic flash with an intensity $I_0 R_{REF}$, where R_{REF} is the reflectivity of the reference piece, and likewise, the workpiece **106**, which in this case is the wafer **120**, reflects the diagnostic flash with intensity $\alpha I_0 R_{WAF}$. The data values of the corrected reflectivity image produced by the imaging device **162**, or more particularly, by individual photodiodes of the InGaAs photodiode array corresponding to the central region **170** of the workpiece **106** and by photodiodes corresponding to the reference piece **142**, are used to calculate and store a ratio of the intensity reflected by the workpiece (in this case, the wafer) to the intensity reflected by the reference piece, namely, $RATIO_{WAF} = \alpha I_0 R_{WAF} / I_0 R_{REF} = \alpha R_{WAF} / R_{REF}$. The resulting ratio value is then stored in the workpiece ratio register **270**.

Block **710** then directs the processor circuit to identify the directional reflectivity R_{WAF} of the wafer **120**. In this regard, as $Ratio_{WAF}/Ratio_{STD}=R_{WAF}/R_{STD}$, the directional reflectivity R_{WAF} of the wafer is then solved from the stored ratios (i.e., the contents $RATIO_{STD}$ and $RATIO_{WAF}$ of the standard ratio register **266** and the workpiece ratio register **270** respectively) and the known reflectivity of the standard (i.e., the contents of the standard reflectivity store **264**), namely, $R_{WAF}=Ratio_{WAF}R_{STD}/Ratio_{STD}$. Block **710** directs the processor circuit **110** to store the directional reflectivity R_{WAF} of the workpiece in the directional reflectivity register **272**.

Block **720** then directs the processor circuit **110** to generate a scattering correction, and to apply the scattering correction to the directional reflectivity R_{WAF} to obtain the hemispherical reflectivity of the substrate side **124** of the wafer **120**.

In this regard, the scattering correction may be determined or pre-determined from the geometry of the system **100** and the nature of the substrate side **124** of the wafer **120**. Due to the fact that the substrate side **124** is typically not a perfect specular reflector, radiation incident on the substrate side at angle θ will not be perfectly reflected at angle θ, but rather, will be reflected over an angle $\theta \pm \Delta\theta$, where $\Delta\theta$ is the difference between specular and actual reflection.

In this embodiment, the primary region of interest of the substrate side **124** is the central region **170**, which will be mapped onto a set Γ of diodes of the imaging device **162**. However, due to scattering, the reflected diagnostic flash from the central region **170** will typically be mapped onto a somewhat larger set Π of diodes, corresponding to a larger surrounding central region **172** of the wafer **120**. For each of the diodes Π corresponding to this larger surrounding central region **172**, a unique $\Delta\theta$ is calculated, from the known geometry of the system **100**, including the relative angles of the diagnostic illumination source **160** and the imaging device **162**. Such $\Delta\theta$ values for each of these diodes may be obtained by applying standard scattering theories.

For example, where an illuminated image of the substrate side **124** of the wafer **120** has been obtained using the diagnostic illumination source **160** and the imaging device **162** (such as the corrected reflectivity image as described in connection with block **700** above, for example), the $\Delta\theta$ value for the i^{th} one of the diodes Π may be calculated as follows:

$$\Delta\theta_i = \arctan\left(\frac{d_i}{r}\right)$$

where d_i is the distance from the brightest diode in the image to the i^{th} diode, measured in "wafer units" (i.e. the dimensions of the real wafer **120**), and r is the distance from the wafer to the effective center of the imaging device **162**. In order to calculate d_i correctly, the image dimensions must be calibrated to the correct x and y sizes of the imaged area. Accordingly, such $\Delta\theta$ values may be pre-calculated and stored if desired, or alternatively, may be produced by the processor circuit **110** under the direction of block **720** of the hemispherical reflectivity routine. In either case, in this embodiment, the $\Delta\theta$ values are temporarily stored in the scattering values register **274**.

Block **720** directs the processor circuit **110** to generate a scattering correction, in response to the $\Delta\theta$ values and the corrected reflectivity image obtained above at block **700**. More particularly, where the corrected reflected intensity data value corresponding to the i^{th} diode is denoted I_i, block **720** directs the processor circuit **110** to calculate a scattering correction S, as follows:

$$S = \frac{\sum_{i \in \Pi} \left(\frac{I_i}{\cos^3 \Delta\theta_i} \right)}{\sum_{i \in \Pi} I_i}, S \geq 1$$

The above scattering correction is an empirical correlation for weak scatters. Alternatively, other types of scattering corrections may be substituted. Such alternatives may be particularly desirable if other types of wafers or workpieces are substituted for the wafer **120**.

The scattering correction S is then stored in the scattering correction register **276**. Block **720** further directs the processor circuit **110** to apply the scattering correction to the directional reflectance R_{WAF} to obtain the hemispherical reflectance R_H of the substrate side **124** of the wafer **120**, as $R_H=SR_{WAF}$. Block **720** directs the processor circuit **110** to store the hemispherical reflectivity R_H in the hemispherical reflectivity register **278**.

Block **730** then directs the processor circuit **110** to transmit the hemispherical reflectivity value R_H to the fast radiometer **164**, for use in producing emissivity-compensated temperature measurements of the substrate side **124** of the wafer **120**, as discussed below in connection with the substrate temperature routine **318**. However, despite the relatively fast sampling rate of the fast radiometer **164**, which generates a new substrate temperature value every millisecond, it is not necessary for the hemispherical reflectivity routine **224** to cause the processor circuit **110** to update the hemispherical reflectivity value at such a high rate. In this regard, it will be appreciated that emissivity (and hence reflectivity) varies somewhat weakly with temperature. Accordingly, depending on the required accuracy of the particular application, it may suffice for the interval between successive hemispherical reflectivity values to significantly exceed the interval between successive temperature values produced by the fast radiometer. Thus, for some applications, it may be sufficient to update the hemispherical reflectivity value at a rate of **10** Hz, or even **1** Hz, for example.

Thus, following execution of block **730**, block **740** directs the processor circuit **110** to determine whether the thermal cycle has ended, and if not, the processor circuit is

directed to wait for an acceptable refreshing interval, such as 100 ms or 1 s, for example, and is then directed back to blocks 700 to 730 to generate a new hemispherical reflectivity value as described above. Such processing continues until the thermal cycle has ended and the wafer has cooled back down to below the threshold temperature (in this embodiment, roughly 700 °C) and thus ceases to be opaque to the 1450 nm diagnostic wavelength.

Substrate Temperature Routine

Referring to Figures 1, 3 and 8, the substrate temperature routine is shown at 318 in Figure 8. Generally, the substrate temperature routine 318 configures the processor circuit 114 of the fast radiometer 164 to identify the temperature of the second surface 118 of the workpiece 106. More particularly, the processor circuit 114 is configured to identify the temperature of the second surface 118 in response to the hemispherical reflectivity of the second surface, and radiation thermally emitted by the second surface.

The substrate temperature routine commences with a first block 800 of codes, which directs the processor circuit 114 to await receipt of an initial hemispherical reflectivity value R_H from the processor circuit 110, as discussed above in connection with the hemispherical reflectivity routine.

Following receipt of this initial hemispherical reflectivity value, block 802 directs the processor circuit 114 to store the received R_H value in the hemispherical reflectivity register 320.

Block 804 then directs the processor circuit 114 to measure an intensity of radiation thermally emitted by the substrate side 124 of the wafer 120. More particularly, block 804 directs the processor circuit 114 to measure an intensity $I_{THERMAL}(t)$ of radiation thermally emitted by the central region 170 of the substrate side 124, at the 1450 nm diagnostic wavelength. Unlike the image produced above for scattering

purposes, this measurement is synchronized so as to be performed at a time when the substrate side **124** is not being illuminated by a diagnostic flash, and thus, the only radiation detectable by the radiometer **164** is radiation thermally emitted by the hot wafer **120**. (It will be recalled that due to the operation of the water-cooled window **156**, the irradiance produced by the pre-heating device **150** does not include wavelengths at the diagnostic wavelength, and thus, even if the pre-heating device **150** is actively irradiating the wafer **120**, any reflections of such irradiance will not be detected by the radiometer **164**.) To achieve this, the processor circuit **114** is directed to monitor signals received from the A/D converter **310**, representing **20**-bit samples of the amplified output of the photodiode **306**, unless a synchronization signal received from the network **292** indicates that the diagnostic illumination source **160** is currently flashing, in which case the measurement of such thermally emitted radiation is delayed until the diagnostic illumination source has been switched off.

Block **806** then directs the processor circuit **114** to identify the temperature of the substrate side **124** of the wafer **120**, in response to the thermal emission intensity value measured at block **804** and the hemispherical reflectivity value received from the processor circuit **110**. More particularly, the measured thermal emission intensity value $I_{THERMAL}(t)$ is used to calculate the instantaneous temperature of the central region **170** of the substrate side **124** of the wafer **120**, as follows:

$$T_{Substrate}(t) = \frac{hc}{\lambda k \ln\left(1 + \frac{2\pi c^2 h \Delta_\lambda \varepsilon_H}{I_{thermal}\lambda^5}\right)}$$

where

$T_{SUBSTRATE}(t)$= instantaneous temperature of the substrate side **124** at the central region **170** at time t;

$I_{THERMAL}(t)$= measured intensity of radiation thermally emitted by the substrate side **124** at the central region **170** at time t;

ε_H = emissivity of the substrate side **124** in the direction of the diagnostic flash, equal to $\kappa(1\text{-}R_H)$ where:

R_H is the hemispherical reflectivity of the substrate side, as discussed above (it will be recalled that the wafer is opaque to the diagnostic wavelength at all temperatures at which this routine is executed, and hence transmissivity is zero and may be ignored in obtaining emissivity from the hemispherical reflectivity value); and

κ is a system constant accounting for the differences in the chamber return between the fast radiometer and the imaging device. For an ideal system κ=**1**, although in the present embodiment, wherein the workpiece includes a **300** mm diameter polished silicon wafer, and the measurement devices are those described herein, $\kappa\cong$**0.9**.

λ = diagnostic wavelength at which $I_{THERMAL}(t)$ was measured (in this embodiment, λ = **1450** nm);

Δ_λ = bandpass of the fast radiometer **164** (in this embodiment, ± **15** nm); and

c,h,k,e = speed of light, Planck's constant, Boltzmann's constant, Euler's number, respectively.

Block **806** then directs the processor circuit **114** to transmit the substrate side temperature value $T_{SUBSTRATE}(t)$ to the processor circuit **110** of the RSC **112**, for storage in the temperature history store **244** as discussed earlier herein.

Block **808** then directs the processor circuit **114** to determine whether a new hemispherical reflectivity value has been received from the processor circuit **110** via the network **292**, and if so, the processor circuit is directed back to block **802** to store the new reflectivity value in the hemispherical reflectivity register **320** and continue obtaining substrate temperature values using the newly-received reflectivity value. If no new reflectivity value has been received, block **810** directs the processor circuit **114** to determine whether the thermal cycle has ended, and if not, the processor circuit is directed back to block **804** to continue obtaining substrate temperature values using the previously-received and stored hemispherical reflectivity value. Irrespective of whether or not a new hemispherical reflectivity value has been received at block **808**, in this embodiment block **806** is re-executed by the processor circuit **114** once every millisecond, to obtain and transmit a new substrate temperature value. Thus, the processor circuit **114** is configured to repeatedly identify successive values of the temperature of the second surface **118** of the workpiece **106** at successive respective times, and to transmit such values to the processor circuit **110** which stores these values to generate the temperature history of the workpiece. Such substrate temperature measurement continues until after the thermal processing cycle (including the pre-heating cycle, the flash cycle and the subsequent cooling stage) has ended, and the wafer has cooled to a sufficiently cold temperature that it is no longer opaque to the **1450** nm diagnostic wavelength.

Real-Time Device Side Temperature Monitoring and Control Routine

Referring to Figures **1**, **4** and **9**, the real-time device side temperature routine is shown at **420** in Figure **9**. Generally, this routine configures the processor circuit **108** of the ultra-fast radiometer **400** to identify a present temperature (in this embodiment, $T_{DEVICE}(t)$) of the first surface **104** of the workpiece **106**, in response to the present intensity of radiation thermally emitted from the first surface **104** and at least one previous thermal property of the first surface at a respective previous time. More particularly, in this embodiment the at least one previous thermal property includes a

previous temperature of the first surface **104**, and a previous intensity of radiation thermally emitted from the first surface at the time the first surface was at the previous temperature. More particularly still, in the present embodiment, the at least one previous thermal property includes the previous temperature T_{DEVICE} (t_0) of the device side **122** of the wafer **120** immediately prior to the commencement of the irradiance flash, and the corresponding previous intensity $I_{DEVICE}(t_0)$ of thermal emission from the device side immediately prior to the commencement of the irradiance flash.

In the present embodiment, the processor circuit **108** is directed to identify such present temperature values $T_{DEVICE}(t)$ during the irradiance flash, at a rate which is fast compared to the duration of the flash. Thus, in the present embodiment, as the A/D converter **412** samples the amplified signal from the photodiode **406** at a rate of **1** MHz, up to **1000** successive temperature values can be produced during the course of a one-millisecond flash, for example, each successive temperature value representing the temperature of the device side at the next successive one-microsecond interval during the flash. Such real-time temperature values may be used for feedback control of the flash itself, if desired. Alternatively, even if these real-time temperature values are not used for feedback control of the flash, they may be useful for analysis after the flash is complete, to enable a user of the system to detect any significant inconsistencies in wafer processing.

The real-time device side temperature routine **420** begins with a first block **900** of codes, which directs the processor circuit **108** to continuously measure and store thermal intensity values $I_{DEVICE}(t)$, representing the intensity of radiation thermally emitted by the central region **170** of the device side **122** of the wafer **12**, at successive instants in time. Again, in the present embodiment, as the A/D converter samples the amplified signal from the photodiode **406** at **1** MHz, up to a million such values can be stored every second, if desired. The processor circuit **108** is directed to store such

thermal intensity values and their corresponding times, in the device side thermal emission intensity store **430**.

Block **910** directs the processor circuit **108** to receive, from the processor circuit **110** of the RSC **112**, an initial device-side temperature value $T_{DEVICE}(t_0)$, and to store the received value in the initial device-side temperature register **432**. Referring back to Figure **6**, it will be recalled that this value $T_{DEVICE}(t_0)$ represents the device side temperature immediately before the commencement of the heating flash produced by the irradiance system, and is transmitted to the processor circuit **108** approximately simultaneously with the commencement of the flash cycle. Upon receiving and storing the initial device-side temperature value $T_{DEVICE}(t_0)$, block **910** also directs the processor circuit **108** to store a corresponding simultaneous device-side thermal emission intensity value $I_{DEVICE}(t_0)$ in the initial device-side thermal intensity register **434**.

Thus, approximately simultaneously with the storage of these initial temperature and intensity values by the processor circuit **108**, the irradiance system commences the flash cycle, exposing the device side **122** of the wafer **120** to a high-energy flash having a duration on the order of one millisecond, thereby rapidly heating the device side **122** of the wafer at a much fast rate than a rate of thermal conduction in the wafer, so that only a shallow layer in the vicinity of the device side **122** is heated to the final annealing temperature, while the bulk of the wafer **120** remains close to the intermediate temperature.

Blocks **920** and **930** then direct the processor circuit **108** to measure the temperature of the device-side **124** at the next successive instant (in this embodiment, the next successive one-microsecond interval) during the flash cycle.

To achieve this, block **920** directs the processor circuit **108** to measure and store a real-time intensity value $I_{DEVICE}(t)$, representing the intensity of radiation thermally emitted by the central region **170** of the device side **122** of the wafer **120**. To achieve

this, the processor circuit **108** receives, from the A/D converter **412**, a 16-bit sample of the amplified signal from the photodiode **406**, and stores it in the device side thermal emission intensity store **430** as described above. (If applicable, the concurrently-running dynamic calibration routine **422** may direct the processor circuit **108** to adjust the received sample value prior to storage, based on the signals received from the internal reference device **450**).

Block **930** then directs the processor circuit **108** to identify the present real-time temperature of the central region **170** of the device side **122**, in response to the previous thermal properties of the device side. More particularly, block **930** directs the processor circuit **108** to calculate the present real-time device side temperature as follows:

$$T_{DEVICE}(t) = \frac{hc}{\lambda k \ln\left[\frac{I_{DEVICE}(t_0)}{I_{DEVICE}(t)}\left(e^{hc/\lambda k T_{DEVICE}(t_0)} - 1\right)\right]}$$

where

$T_{DEVICE}(t)$ = real-time temperature of the device side **122** at the central region **170** of the workpiece;

$I_{Device}(t)$ = real-time measurement value produced by the ultra-fast radiometer **400** of the thermal emission intensity from the device side **122** at the central region **170** of the workpiece;

$T_{DEVICE}(t_0)$= instantaneous temperature of the device side **122** at the central region **170**, immediately prior to commencement of the heating flash produced by the irradiance system **180**;

$I_{DEVICE}(t_0)$= instantaneous intensity of thermal emission from the device side **122** at the central region **170**, immediately prior to commencement of the heating flash; and

the remaining variables and constants are as defined above.

In the foregoing calculation at block **930**, it is assumed that the emissivity of the device side **122** remains constant during the flash cycle. Although this assumption is not entirely accurate, the emissivity of similar wafers will vary similarly when subjected to similar thermal cycles. Thus, even if the assumption of constant emissivity introduces a slight measurement error into the device-side temperature measurements in the vicinity of the peak annealing temperature, such errors will be consistently reproduced for similar wafers in similar cycles. Thus, any such errors will not affect the reproducibility of the resulting thermal cycle.

In this embodiment, the execution of blocks **920** and **930** is repeated a significant number of times during the course of the irradiance flash produced by the irradiance system **180**. More particularly, in this embodiment the irradiance flash has a duration on the order of one millisecond, and blocks **920** and **930** are repeated once every microsecond, thereby producing **1000** successive real-time device-side temperature values during the course of the one-millisecond flash cycle. Thus, in the present embodiment, the real-time device side temperature routine configures the processor circuit **108** to repeatedly identify successive values of the present temperature of the first surface **104** in response to successive respective values of the present intensity of radiation thermally emitted by the first surface, while the first surface is being irradiated, or more particularly, while the first surface is being exposed to an irradiance flash having a duration less than a thermal conduction time of the workpiece.

If desired, the real-time device side temperature routine **420** may include instruction codes for directing the processor circuit **108** of the ultra-fast radiometer **400** to control

the power of the irradiance flash produced by the irradiance system, in response to the real-time temperature values.

For example, in the present embodiment, the real-time device side temperature routine **420** includes a further block **940** of codes, which directs the processor circuit **108** to control power supplied to the irradiance system **180** to control the power of the irradiance flash. More particularly, in this embodiment block **940** directs the processor circuit **108** to determine whether at least one pre-defined condition is satisfied. More particularly still, block **940** directs the processor circuit **108** to determine whether the most-recently obtained real-time device side temperature value $T_{DEVICE}(t)$ is greater than or equal to a pre-defined maximum desired temperature of the device side **122** during the course of the flash. If so, block **940** directs the processor circuit **108** to signal the power control system **188** of the irradiance system **180**, to immediately discontinue the remainder of the pulsed discharge of electrical power from the power control system to the flash lamp **182**.

For example, referring to Figure **10**, a power control circuit of the power control system **188** according to one embodiment of the invention is shown generally at **960**. The stored charge that is to be supplied to the flash lamp **182** to produce the irradiance flash is stored in a large capacitor bank, which for ease of illustration is symbolized by a single capacitor **962** in Figure **10**. A switch **964** and an inductor **966** are interposed in series between one plate of the capacitor and one electrode of the flash lamp **182**, and the other electrode of the flash lamp is connected to the other plate of the capacitor. In embodiments where closed-loop feedback control of the flash is not required, the switch **964** need not be easily restored from its conducting state to its open or non-conducting state. Thus, in such embodiments, a silicon controlled rectifier having a holding current less than the expected current discharge during the flash, may be employed as the switch **964**. Alternatively, however, if feedback control is desired with such a circuit, the switch **964** preferably includes a switch type that is easily restored from its conducting state to its non-conducting state while it is in the process of conducting the large expected

discharge current from the capacitor **962**. In such an embodiment, if at block **940** the processor circuit **108** determines that the device side temperature $T_{DEVICE}(t)$ is greater than or equal to the pre-defined maximum desired temperature, the processor circuit **108** is directed to open the switch **964** to discontinue the electrical discharge from the capacitor **962**.

Similarly, if desired, block **940** may direct the processor circuit **108** to periodically compare a real-time device side temperature value $T_{DEVICE}(t)$ with an expected or predicted device side temperature for the same time t during the course of the flash cycle, and may increase or decrease the power supplied by the power control system **188** to the flash lamp **182** so as to minimize any discrepancies between actual and expected device side temperature.

For example, referring to Figure **11**, a power control circuit of the power control system **188** according to a second embodiment of the invention is shown generally at **970**. The capacitor bank that is to be discharged to produce the irradiance flash is again symbolically shown as a single capacitor **962**, for ease of illustration. Along a first electrical pathway **972** connecting one plate of the capacitor **962** to one electrode of the flash lamp, a switch **974** and an inductor **976** are interposed in series. A second electrical pathway **978** connects the other plate of the capacitor to the other electrode of the flash lamp. A resistor **980** and a second switch **982** in series, are connected between the first electrical pathway **972** and the second electrical pathway **978**, with the resistor being connected to the first electrical pathway **972** at a point **984** between the first switch **974** and the inductor **976**, and the second switch **986** being connected to the second electrical pathway **978** at a point **986**. The second switch **982** may include a gate-controlled switch, such as a silicon controlled rectifier, for example. More generally, any suitable switch types may be used as the switches **974** and **982**. When the first switch **974** is initially closed by the processor circuit **110** of the RSC **112** to initiate the flash, the second switch **982** is left open. If at block **940** the processor circuit **108** of the ultra-fast radiometer **400** determines that the device side temperature $T_{DEVICE}(t)$ is higher

than a desired temperature at a given point in time during the flash, block **940** directs the processor circuit **108** to apply a gate signal to the gate of the second switch **982** to close the second switch and cause some of the electrical current discharged by the capacitor **962** to flow through the resistor **980**, thereby reducing the current supplied by the capacitor **962** to the flash lamp **182**.

Similarly, referring to Figure **12**, a power control circuit of the power control system **188** according to a third embodiment of the invention is shown generally at **990**. The capacitor bank that is to be discharged to produce the irradiance flash is again symbolically shown as a single capacitor **962**, for ease of illustration. Along a first electrical pathway **991** connecting a first plate of the capacitor **962** to a first electrode of the flash lamp **182**, a first switch **992**, a first inductor **993**, and a second inductor **994** in parallel with a second switch **995**, are interposed in series. In this regard, the second switch **995** is interposed along an electrical sub-pathway **996** of the first electrical pathway **991**. One end of the electrical sub-pathway **996** is connected to a point **997** interposed between the first inductor **993** and the second inductor **994**. The other end of the electrical sub-pathway **996** is connected to a point **998** interposed between the second inductor **994** and the first plate of the flash lamp **182**. The second switch **995** may include a gate-controlled switch, such as a silicon controlled rectifier, for example. More generally, any suitable switch types may be used as the switches **992** and **995**. A second electrical pathway **999** connects the second plate of the capacitor **962** to the second electrode of the flash lamp **182**. When the first switch **992** is initially closed by the processor circuit **110** of the RSC **112** to initiate the flash, the second switch **995** is left open. If at block **940** the processor circuit **108** of the ultra-fast radiometer **400** determines that the device side temperature $T_{DEVICE}(t)$ is lower than a desired temperature at a given point in time during the flash, block **940** directs the processor circuit **108** to apply a gate signal to the gate of the second switch **995** to close the second switch, thereby increasing the current supplied by the capacitor **962** to the flash lamp **182**.

In this embodiment, irrespective of whether a feedback control block **940** is provided, block **950** directs the processor circuit to determine whether the thermal cycle (including the pre-heating cycle, the flash cycle, and the subsequent cooling stage) has ended, and the wafer has cooled to a sufficiently cold temperature that it is no longer opaque to the **1450** nm diagnostic wavelength. If the thermal cycle has not ended, the processor circuit is directed back to blocks **920** and **930**, which are repeatedly re-executed by the processor circuit **108**, to continue repeatedly identifying the real-time device-side temperature at **1** μs intervals during the irradiance flash and the cooling stage thereafter.

<u>Further Exemplary Alternatives</u>

Referring to Figures **1**, **4**, **6**, **9** and **13**, a system for temperature measurement and for heat-treating a workpiece according to a fourth embodiment of the invention is shown generally at **1000** in Figure **13**. The system **1000** is generally similar to the system **100** shown in Figure **1**, except that an alternative irradiance system **1010** has been substituted for the irradiance system **180**.

In this embodiment, the irradiance system **1010** includes a plurality of irradiance sources shown generally at **1020**, or more particularly, a plurality of arc lamps similar to the flash lamp **182** shown in Figure **1**. The at least one processor circuit (or more particularly, the processor circuit **108** of the ultra-fast radiometer **400**) is configured to activate one of the plurality of irradiance sources only if the present temperature of the first surface is less than a pre-defined threshold.

More particularly, in this embodiment, the irradiance system **1010** includes at least two independent power control systems **1030** and **1040**, each of which is similar to the pulsed discharge power supply unit of the power control system **188** shown in Figure **1**. The first power control system **1030** supplies power to first, second and third arc lamps **1032**, **1034** and **1036**, while the second power control system **1040** supplies power to a fourth arc lamp **1042**. In this embodiment, the first power control system **1030** is activated under the direction of the processor circuit **110** of the RSC

112, as discussed above in connection with block **616** of the temperature monitoring and control routine **226** shown in Figure **6**.

However, in the present embodiment, the second power control system **1040** is not controlled by the RSC **112**. Rather, in this embodiment, the second power control system **1040** is activated by the processor circuit **108** of the ultra-fast radiometer **400** under the direction of block **940** of the real-time device side temperature routine **420** shown in Figure **9**. More particularly, in this embodiment, block **940** directs the processor circuit **108** to activate the second power control system **1040** only if, after a pre-defined interval following the commencement of the flash cycle, the present device side temperature $T_{DEVICE}(t)$ is less than a pre-defined desired temperature. Thus, in this embodiment, the energy discharged to the fourth arc lamp will be adjusted to cause the device side **122** of the wafer to reach the desired temperature.

Alternatively, if desired, the number of flash lamps or other suitable irradiance sources that are under the control of the processor circuit **108** may be varied, if desired.

More generally, while specific embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

What is claimed is:

1. A temperature measurement method comprising:

   a) measuring a present intensity of radiation thermally emitted from a first surface of a workpiece; and

   b) identifying a present temperature of the first surface, in response to the present intensity and at least one previous thermal property of the first surface at a respective previous time.

2. The method of claim 1 wherein the workpiece comprises a semiconductor wafer and the first surface comprises a device side of the wafer.

3. The method of claim 2 wherein identifying comprises identifying the present temperature of the device side while the device side is being irradiated.

4. The method of claim 2 wherein identifying comprises identifying the present temperature of the device side while the device side is being exposed to an irradiance flash having a duration less than a thermal conduction time of the wafer.

5. The method of claim 4 wherein the irradiance flash has a duration less than 10 milliseconds.

6. The method of claim 4 further comprising identifying, at the previous time, the at least one previous thermal property of the first surface, wherein the at least one previous thermal property comprises a previous temperature of the device side of the wafer immediately preceding commencement of the irradiance flash.

7. The method of claim **6** wherein the at least one previous thermal property further comprises a previous intensity of radiation thermally emitted from the device side immediately preceding commencement of the irradiance flash.

8. The method of claim **1** wherein identifying comprises identifying the present temperature of the first surface in response to the present intensity, a previous temperature of the first surface, and a previous intensity of radiation thermally emitted from the first surface at the previous time.

9. The method of claim **1** further comprising identifying, at the previous time, the at least one previous thermal property of the first surface, wherein the at least one previous thermal property comprises a previous temperature of the first surface.

10. The method of claim **9** wherein identifying the previous temperature of the first surface comprises identifying the previous temperature in response to a previous temperature of a second surface of the workpiece unequal to the previous temperature of the first surface.

11. The method of claim **10** wherein identifying the previous temperature of the first surface comprises identifying the previous temperature of the first surface in response to the previous temperature of the second surface and a temperature history of the workpiece.

12. The method of claim **11** wherein the workpiece comprises a semiconductor wafer, the first surface comprises a device side of the wafer, and the second surface comprises a substrate side of the wafer.

13. The method of claim **11** wherein identifying the previous temperature of the first surface comprises using the previous temperature of the second surface and the temperature history to address a look-up table record.

14. The method of claim **11** further comprising identifying, at the previous time, the previous temperature of the second surface.

15. The method of claim **14** wherein identifying the previous temperature of the second surface comprises identifying the previous temperature of the second surface in response to a hemispherical reflectivity of the second surface.

16. The method of claim **15** further comprising measuring the hemispherical reflectivity.

17. The method of claim **16** wherein measuring the hemispherical reflectivity comprises receiving radiation reflected by the second surface at a detector positioned sufficiently far away from the second surface to avoid obstructing the second surface from fields of view of other devices of a system in which the workpiece is located.

18. The method of claim **16** wherein measuring the hemispherical reflectivity comprises receiving radiation reflected by the second surface at a detector positioned a distance from a center of the second surface, the distance being at least as great as one-half of the largest dimension of the workpiece.

19. The method of claim **16** wherein measuring the hemispherical reflectivity comprises measuring a directional reflectivity of the second surface.

20. The method of claim **19** wherein measuring the hemispherical reflectivity further comprises applying a scattering correction to the directional reflectivity to obtain the hemispherical reflectivity.

21. The method of claim **16** wherein identifying the previous temperature of the second surface comprises identifying the previous temperature of the second surface in response to the hemispherical reflectivity of the second surface and radiation thermally emitted by the second surface.

22. The method of claim **20** further comprising generating the scattering correction.

23. The method of claim **14** further comprising repeatedly identifying and storing successive values of the previous temperature of the second surface at successive respective times, to generate the temperature history of the workpiece.

24. The method of claim **1** further comprising repeatedly identifying successive values of the present temperature of the first surface in response to successive respective values of the present intensity of radiation thermally emitted by the first surface.

25. The method of claim **24** wherein repeatedly identifying comprises repeatedly identifying the successive values of the present temperature of the first surface while the first surface is being irradiated.

26. The method of claim **24** wherein repeatedly identifying comprises repeatedly identifying the successive values of the present temperature of the first surface while the first surface is being exposed to an irradiance flash having a duration less than a thermal conduction time of the workpiece.

27. The method of claim **1** wherein measuring comprises measuring the present intensity in a wavelength band in which an irradiance spectrum incident upon the first surface has negligible intensity.

28. The method of claim **27** further comprising removing the wavelength band from the irradiance spectrum incident upon the first surface.

29. The method of claim **19** wherein measuring the directional reflectivity comprises measuring reflected intensity in an illumination wavelength band in

which a heating irradiance spectrum incident upon the second surface has negligible intensity.

30. The method of claim **29** further comprising removing the illumination wavelength band from the heating irradiance spectrum.

31. A method of heat-treating a workpiece, the method comprising the method of claim **1** and further comprising controlling a power of an irradiance flash incident on the first surface of the workpiece, in response to the present temperature of the first surface.

32. The method of claim **31** wherein controlling comprises controlling power supplied to at least one irradiance source operable to produce the irradiance flash.

33. The method of claim **31** wherein controlling comprises activating one of a plurality of irradiance sources only if the present temperature of the first surface is less than a pre-defined threshold.

34. The method of any one of claim **1**, claim **8** to claim **11**, and claim **13** to claim **33**, wherein the workpiece comprises a semiconductor wafer and the first surface comprises a device side of the wafer.

35. A temperature measurement system comprising:

a) a measurement device configured to measure a present intensity of radiation thermally emitted from a first surface of a workpiece; and

b) at least one processor circuit in communication with the measurement device, the at least one processor circuit configured to identify a present temperature of the first surface, in response to the present intensity and at least one previous thermal property of the first surface at a respective previous time.

36. The system of claim **35** wherein the workpiece comprises a semiconductor wafer and the first surface comprises a device side of the wafer.

37. The system of claim **36** further comprising an irradiance system operable to irradiate the device side of the wafer, and wherein the measurement device and the at least one processor circuit are configured to measure the present intensity and identify the present temperature of the device side while the device side is being irradiated by the irradiance system.

38. The system of claim **37** wherein the irradiance system is operable to expose the device side to an irradiance flash having a duration less than a thermal conduction time of the wafer, and wherein the measurement device and the at least one processor circuit are configured to measure the present intensity and identify the present temperature during the irradiance flash.

39. The system of claim **38** wherein the irradiance system is operable to produce the irradiance flash to have a duration on the order of **10** milliseconds or less.

40. The system of claim **38** wherein the irradiance system is operable to produce the irradiance flash to have a duration on the order of **1** millisecond.

41. The system of claim **38** wherein the at least one processor circuit is configured to identify, at the previous time, the at least one previous thermal property of the first surface, wherein the at least one previous thermal property comprises a previous temperature of the device side of the wafer immediately preceding commencement of the irradiance flash.

42. The system of claim **41** wherein the at least one previous thermal property further comprises a previous intensity of radiation thermally emitted from the device side immediately preceding commencement of the irradiance flash.

43. The system of claim 35 wherein the at least one processor circuit is configured to identify, at the previous time, the present temperature of the first surface in response to the present intensity, a previous temperature of the first surface, and a previous intensity of radiation thermally emitted from the first surface at the time the first surface was at the previous temperature.

44. The system of claim 35 wherein the at least one processor circuit is configured to identify, at the previous time, the at least one previous thermal property of the first surface, wherein the at least one previous thermal property comprises a previous temperature of the first surface.

45. The system of claim 44 wherein the at least one processor circuit is configured to identify the previous temperature of the first surface in response to a previous temperature of a second surface of the workpiece unequal to the previous temperature of the first surface.

46. The system of claim 45 wherein the at least one processor circuit is configured to identify the previous temperature of the first surface in response to the previous temperature of the second surface and a temperature history of the workpiece.

47. The system of claim 46 wherein the workpiece comprises a semiconductor wafer, the first surface comprises a device side of the wafer, and the second surface comprises a substrate side of the wafer.

48. The system of claim 46 wherein the at least one processor circuit is configured to use the previous temperature of the second surface and the temperature history to address a look-up table record, to identify the previous temperature of the first surface.

49. The system of claim **46** wherein the at least one processor circuit is configured to identify, at the previous time, the previous temperature of the second surface.

50. The system of claim **49** wherein the at least one processor circuit is configured to identify the previous temperature of the second surface in response to a hemispherical reflectivity of the second surface.

51. The system of claim **50** further comprising a second measurement device in communication with the at least one processor circuit, wherein the at least one processor circuit is configured to cooperate with the second measurement device to measure the hemispherical reflectivity of the second surface.

52. The system of claim **51** wherein the second measurement device comprises a radiation detector configured to receive radiation reflected by the second surface, the detector being positioned sufficiently far away from the second surface to avoid obstructing the second surface from fields of view of other devices of the system.

53. The system of claim **51** wherein the second measurement device comprises a radiation detector configured to receive radiation reflected by the second surface, the detector being positioned a distance from a center of the second surface at least as great as one-half of the largest dimension of the workpiece.

54. The system of claim **51** wherein the second measurement device comprises a detector configured to measure a directional reflectivity of the second surface.

55. The system of claim **54** wherein the at least one processor circuit is configured to apply a scattering correction to the directional reflectivity to obtain the hemispherical reflectivity.

56. The system of claim **51** wherein the at least one processor circuit is configured to identify the previous temperature of the second surface in response to the hemispherical reflectivity of the second surface and radiation thermally emitted by the second surface.

57. The system of claim **55** wherein the at least one processor circuit is configured to generate the scattering correction.

58. The system of claim **49** wherein the at least one processor circuit is configured to repeatedly identify and store successive values of the previous temperature of the second surface at successive respective times, to generate the temperature history of the workpiece.

59. The system of claim **35** wherein the at least one processor circuit is configured to repeatedly identify successive values of the present temperature of the first surface in response to successive respective values of the present intensity of radiation thermally emitted by the first surface.

60. The system of claim **59** wherein the at least one processor circuit is configured to repeatedly identify the successive values of the present temperature of the first surface while the first surface is being irradiated.

61. The system of claim **59** wherein the at least one processor circuit is configured to repeatedly identify the successive values of the present temperature of the first surface while the first surface is being exposed to an irradiance flash having a duration less than a thermal conduction time of the workpiece.

62. The system of claim **35** wherein the measurement device is configured to measure the present intensity in a wavelength band in which an irradiance spectrum incident upon the first surface has negligible intensity.

63. The system of claim **62** further comprising a filtering device configured to remove the wavelength band from the irradiance spectrum incident upon the first surface.

64. The system of claim **63** wherein the filtering device comprises a water-cooled window interposed between the first surface and a source of the irradiance spectrum

65. The system of claim **54** wherein the second measurement device is configured to measure the directional reflectivity in an illumination wavelength band in which a heating irradiance spectrum incident upon the second surface has negligible intensity.

66. The system of claim **65** further comprising a filtering device configured to remove the illumination wavelength band from the heating irradiance spectrum.

67. The system of claim **66** wherein the filtering device comprises a water-cooled window interposed between the second surface and a source of the heating irradiance spectrum.

68. A system for heat-treating a workpiece, the system comprising the system of claim **35** and further comprising an irradiance system operable to expose the first surface of the workpiece to an irradiance flash incident thereon, wherein the at least one processor circuit is configured to control a power of the irradiance flash in response to the present temperature of the first surface.

69. The system of claim **68** wherein the at least one processor circuit is configured to control power supplied to the irradiance system to control the power of the irradiance flash.

70. The system of claim **68** wherein the irradiance system comprises a plurality of irradiance sources, and wherein the at least one processor circuit is configured to activate one of the plurality of irradiance sources only if the present temperature of the first surface is less than a pre-defined threshold.

71. The system of any one of claim **35**, claim **43** to claim **46**, and claim **48** to claim **70**, wherein the workpiece comprises a semiconductor wafer and the first surface comprises a device side of the wafer.

72. The system of any one of claim **35** to claim **70** wherein the measurement device comprises a radiometer.

73. The system of claim **72** wherein the radiometer comprises a high-speed InGaAs photodiode.

74. The system of any one of claim **51** to claim **57** and claim **65** to claim **67**, wherein the second measurement device comprises an imaging device.

75. The system of claim **74** wherein the imaging device comprises an InGaAs photodiode array.

76. A temperature measurement system comprising:

a) means for measuring a present intensity of radiation thermally emitted from a first surface of a workpiece; and

b) means for identifying a present temperature of the first surface, in response to the present intensity and at least one previous thermal property of the first surface at a respective previous time.

77. The system of claim **76** further comprising means for identifying, at the previous time, the at least one previous thermal property of the first surface,

wherein the at least one previous thermal property comprises a previous temperature of the first surface.

78. The system of claim **77** wherein the means for identifying the previous temperature comprises means for identifying the previous temperature of the first surface in response to a previous temperature of a second surface of the workpiece unequal to the previous temperature of the first surface.

79. The system of claim **78** wherein the means for identifying the previous temperature of the first surface comprises means for identifying the previous temperature of the first surface in response to the previous temperature of the second surface and a temperature history of the workpiece.

80. The system of claim **79** further comprising means for identifying, at the previous time, the previous temperature of the second surface.

81. The system of claim **80** wherein the means for identifying the previous temperature of the second surface comprises means for identifying the previous temperature of the second surface in response to a hemispherical reflectivity of the second surface.

82. The system of claim **81** further comprising means for measuring the hemispherical reflectivity.

83. The system of any one of claim **76** to claim **82** wherein the workpiece comprises a semiconductor wafer and the first surface comprises a device side of the wafer.

84. A system for heat-treating a workpiece, the system comprising the system of claim **76** and further comprising means for controlling a power of an irradiance flash incident on the first surface of the workpiece, in response to the present temperature of the first surface.

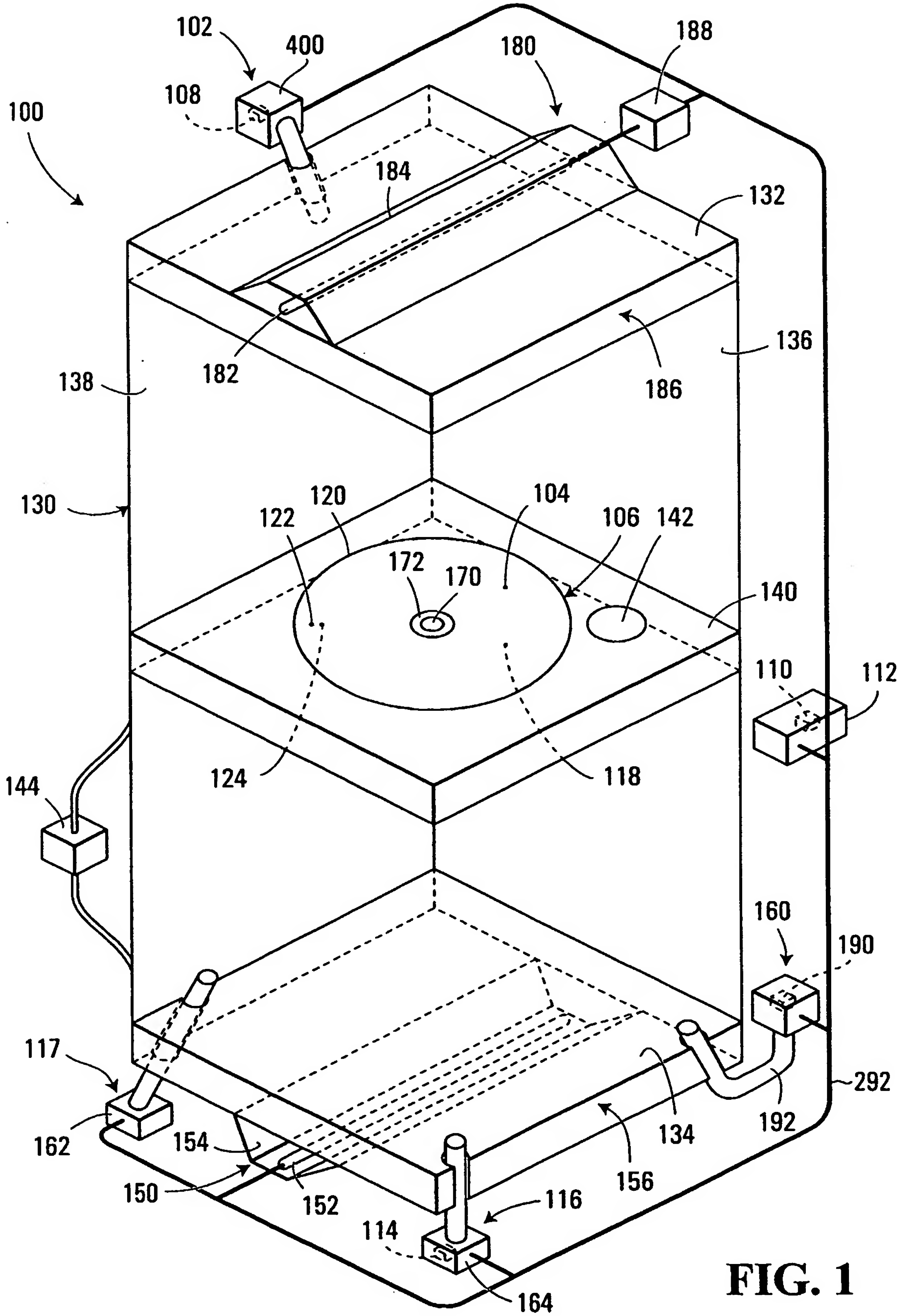
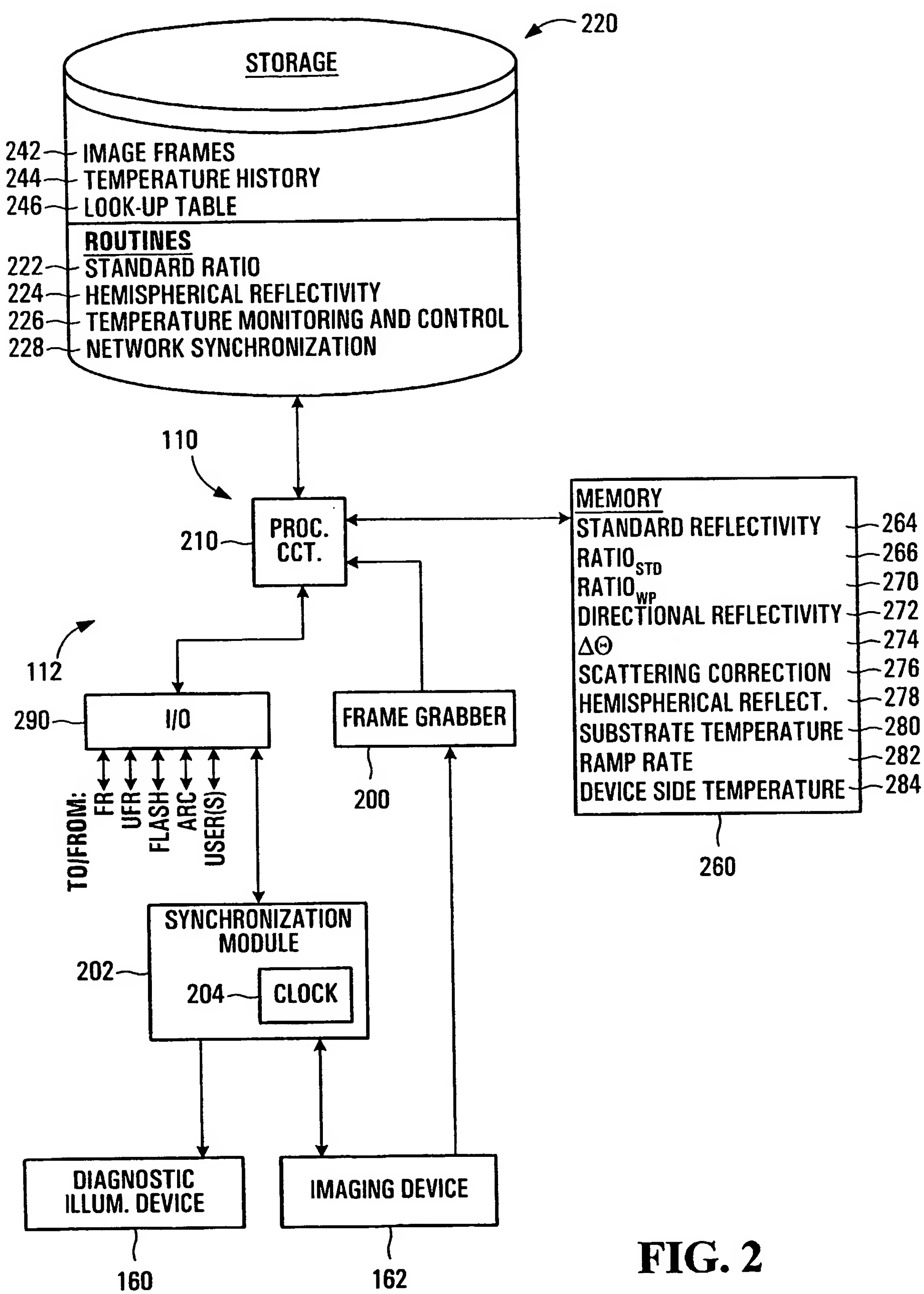

102
400
108
180
188
100
184
132
136
138
182
186
130
120
104
106
142
122
172
170
140
110
112
144
124
118
160
190
117
292
134
192
162
154
156
150
152
116
114
164

FIG. 1



220
STORAGE
242 IMAGE FRAMES
244 TEMPERATURE HISTORY
246 LOOK-UP TABLE
ROUTINES
222 STANDARD RATIO
224 HEMISPHERICAL REFLECTIVITY
226 TEMPERATURE MONITORING AND CONTROL
228 NETWORK SYNCHRONIZATION
110
210 PROC. CCT.
MEMORY
STANDARD REFLECTIVITY 264
RATIO STD 266
RATIO WP 270
DIRECTIONAL REFLECTIVITY 272
ΔΘ 274
SCATTERING CORRECTION 276
HEMISPHERICAL REFLECT. 278
SUBSTRATE TEMPERATURE 280
RAMP RATE 282
DEVICE SIDE TEMPERATURE 284
260
112
290 I/O
FRAME GRABBER
200
TO/FROM: FR UFR FLASH ARC USER(S)
SYNCHRONIZATION MODULE
202
204 CLOCK
DIAGNOSTIC ILLUM. DEVICE
160
IMAGING DEVICE
162

FIG. 2

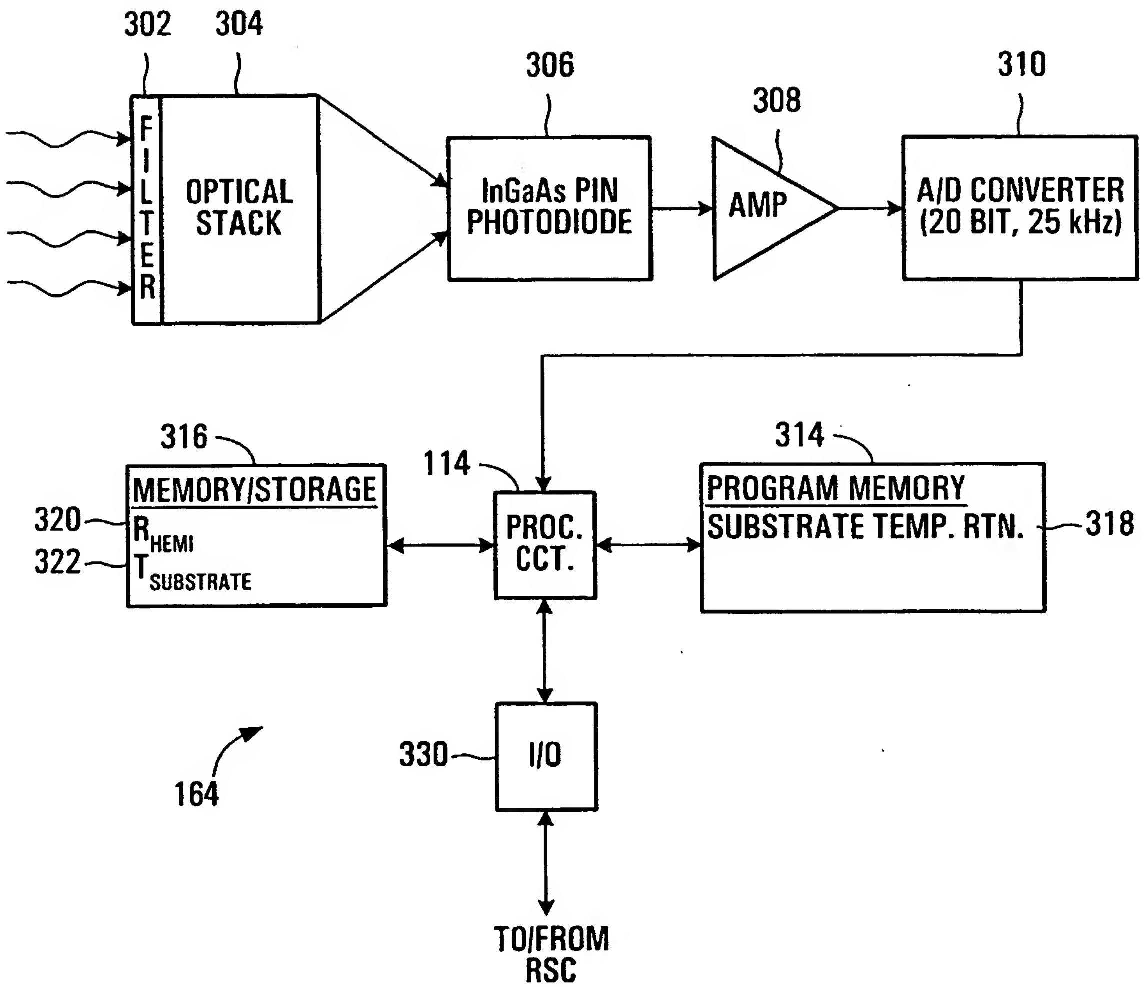

302
304
FILTER
OPTICAL STACK
306
InGaAs PIN PHOTODIODE
308
AMP
310
A/D CONVERTER (20 BIT, 25 kHz)
316
MEMORY/STORAGE
320
R HEMI
322
T SUBSTRATE
114
PROC. CCT.
314
PROGRAM MEMORY
SUBSTRATE TEMP. RTN.
318
330
I/O
164
TO/FROM RSC

FIG. 3

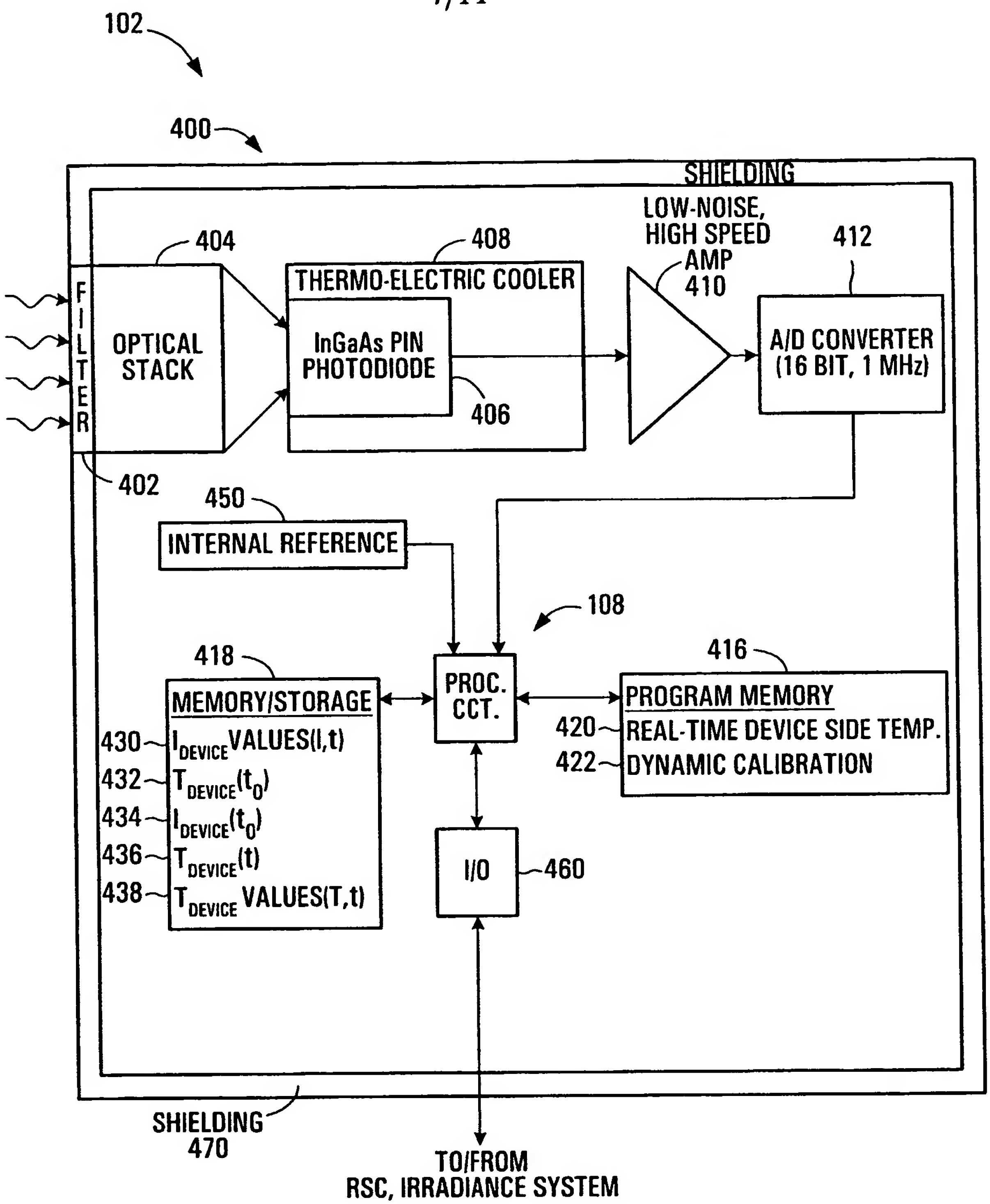

102
400
SHIELDING
LOW-NOISE, HIGH SPEED AMP 410
404
408
412
THERMO-ELECTRIC COOLER
FILTER
OPTICAL STACK
InGaAs PIN PHOTODIODE
406
A/D CONVERTER (16 BIT, 1 MHz)
402
450
INTERNAL REFERENCE
108
418
416
MEMORY/STORAGE
PROC. CCT.
PROGRAM MEMORY
420 REAL-TIME DEVICE SIDE TEMP.
422 DYNAMIC CALIBRATION
430 I DEVICE VALUES(I,t)
432 T DEVICE (t0)
434 I DEVICE (t0)
436 T DEVICE (t)
438 T DEVICE VALUES(T,t)
I/O
460
SHIELDING 470
TO/FROM RSC, IRRADIANCE SYSTEM

FIG. 4

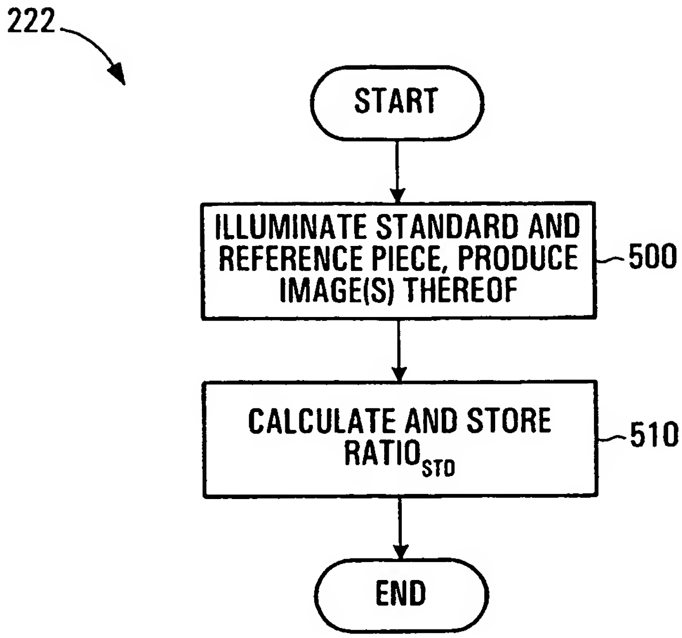
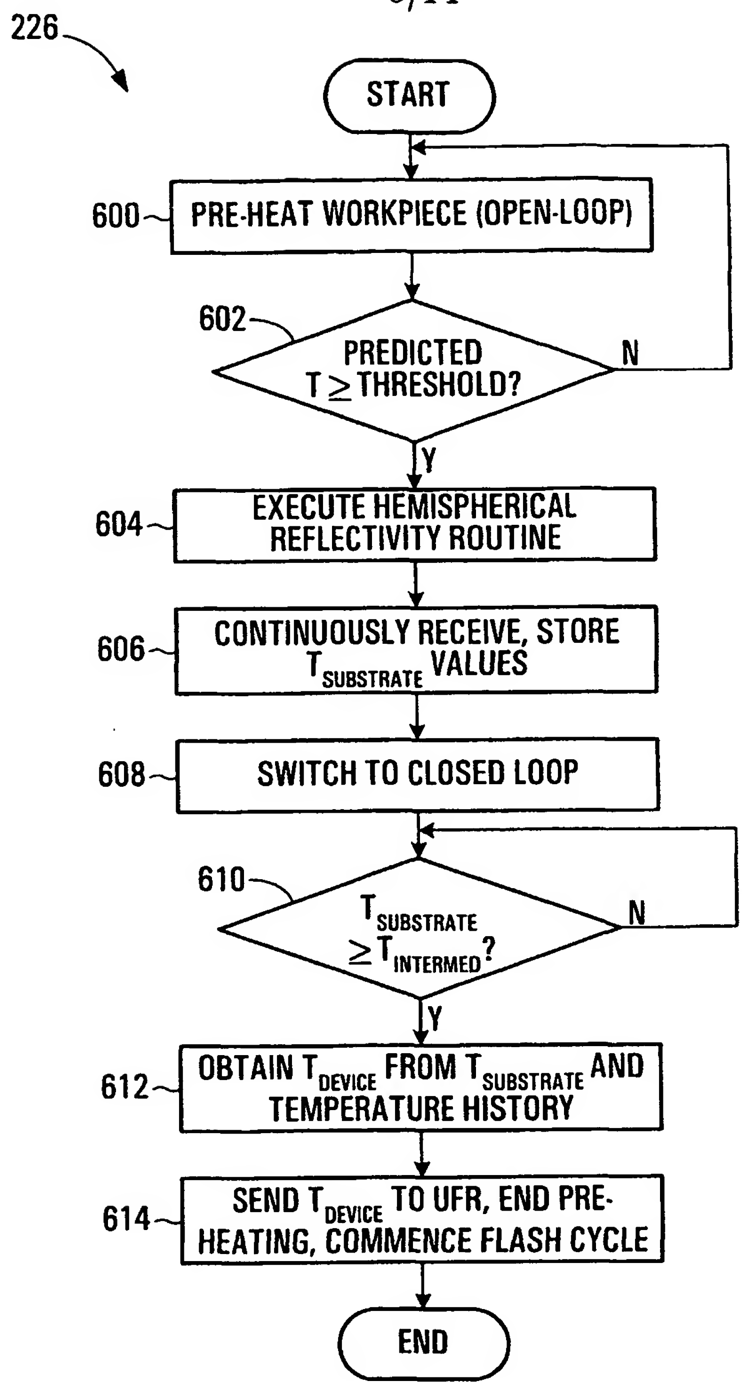

222
START
ILLUMINATE STANDARD AND REFERENCE PIECE, PRODUCE IMAGE(S) THEREOF
500
CALCULATE AND STORE RATIO STD
510
END

FIG. 5



226
START
600
PRE-HEAT WORKPIECE (OPEN-LOOP)
602
PREDICTED T ≥ THRESHOLD?
N
Y
604
EXECUTE HEMISPHERICAL REFLECTIVITY ROUTINE
606
CONTINUOUSLY RECEIVE, STORE $T_{SUBSTRATE}$ VALUES
608
SWITCH TO CLOSED LOOP
610
$T_{SUBSTRATE} \geq T_{INTERMED}$?
N
Y
612
OBTAIN T_{DEVICE} FROM $T_{SUBSTRATE}$ AND TEMPERATURE HISTORY
614
SEND T_{DEVICE} TO UFR, END PRE-HEATING, COMMENCE FLASH CYCLE
END

FIG. 6

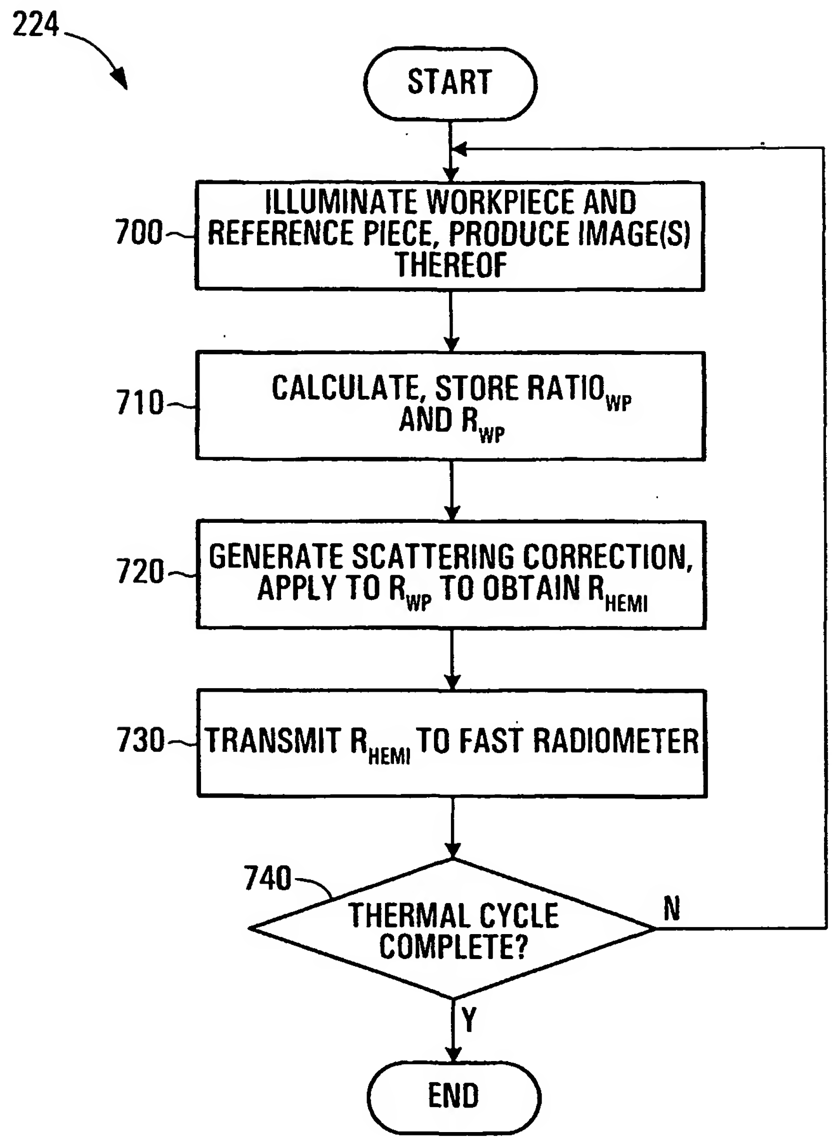

224
START
ILLUMINATE WORKPIECE AND REFERENCE PIECE, PRODUCE IMAGE(S) THEREOF
700
CALCULATE, STORE RATIO$_{WP}$ AND R$_{WP}$
710
GENERATE SCATTERING CORRECTION, APPLY TO R$_{WP}$ TO OBTAIN R$_{HEMI}$
720
TRANSMIT R$_{HEMI}$ TO FAST RADIOMETER
730
740
THERMAL CYCLE COMPLETE?
N
Y
END

FIG. 7

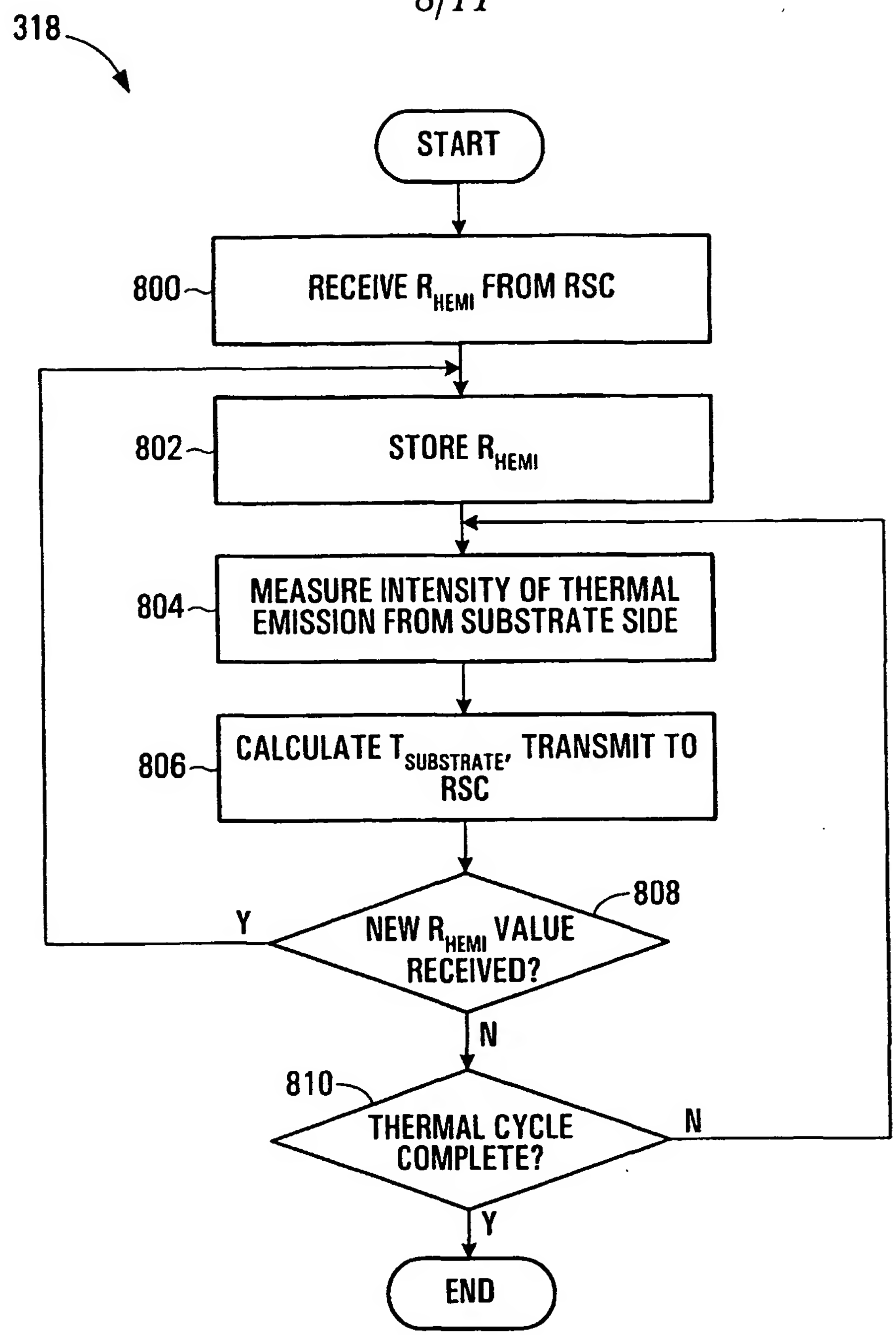

318
START
800
RECEIVE R_{HEMI} FROM RSC
802
STORE R_{HEMI}
804
MEASURE INTENSITY OF THERMAL EMISSION FROM SUBSTRATE SIDE
806
CALCULATE $T_{SUBSTRATE}$, TRANSMIT TO RSC
808
NEW R_{HEMI} VALUE RECEIVED?
Y
N
810
THERMAL CYCLE COMPLETE?
N
Y
END

FIG. 8

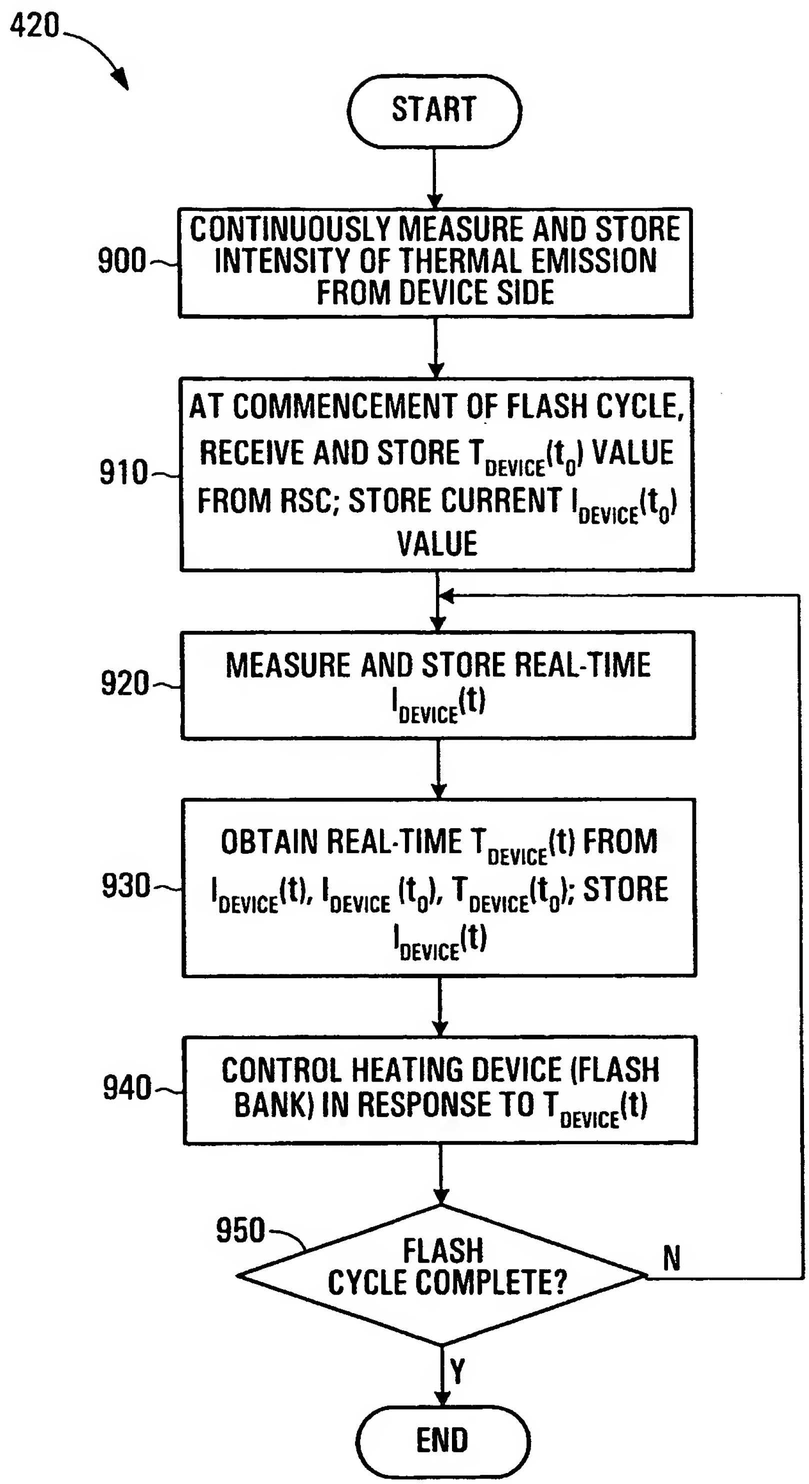

420
START
900
CONTINUOUSLY MEASURE AND STORE INTENSITY OF THERMAL EMISSION FROM DEVICE SIDE
910
AT COMMENCEMENT OF FLASH CYCLE, RECEIVE AND STORE $T_{DEVICE}(t_0)$ VALUE FROM RSC; STORE CURRENT $I_{DEVICE}(t_0)$ VALUE
920
MEASURE AND STORE REAL-TIME $I_{DEVICE}(t)$
930
OBTAIN REAL-TIME $T_{DEVICE}(t)$ FROM $I_{DEVICE}(t)$, $I_{DEVICE}(t_0)$, $T_{DEVICE}(t_0)$; STORE $I_{DEVICE}(t)$
940
CONTROL HEATING DEVICE (FLASH BANK) IN RESPONSE TO $T_{DEVICE}(t)$
950
FLASH CYCLE COMPLETE?
N
Y
END

FIG. 9

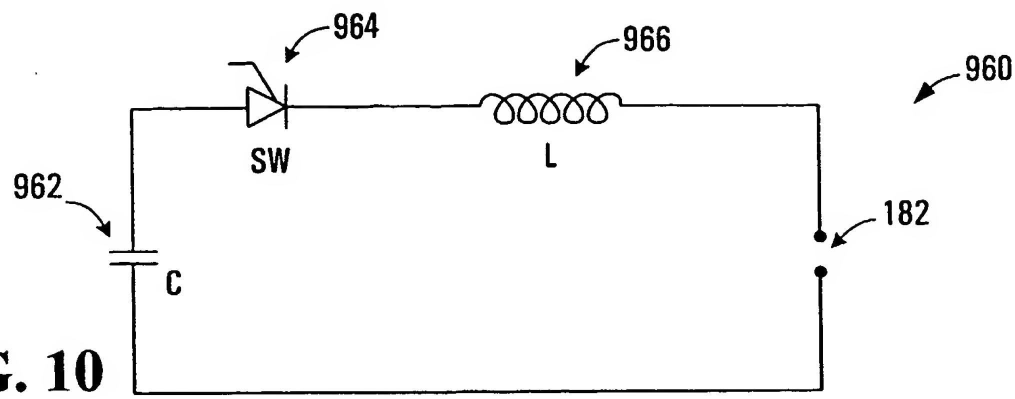


FIG. 10

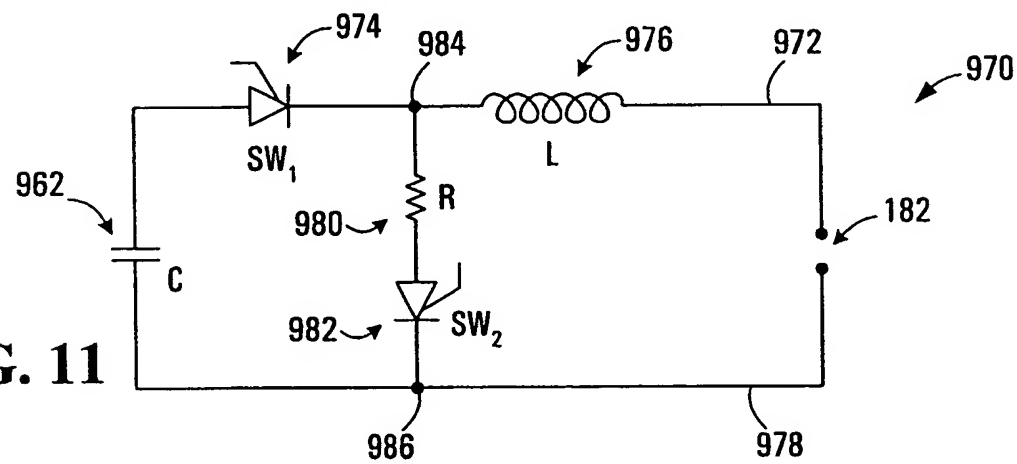


FIG. 11

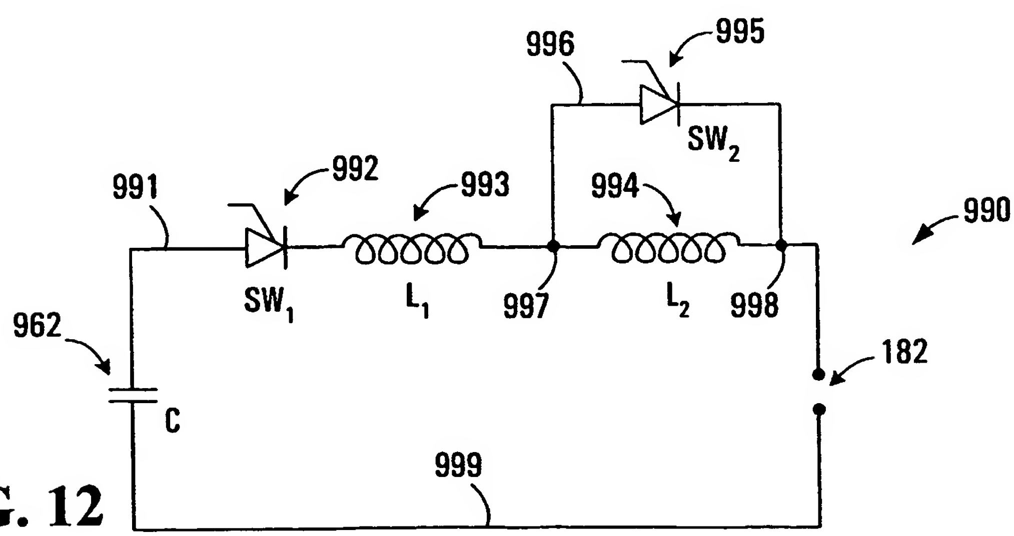


FIG. 12

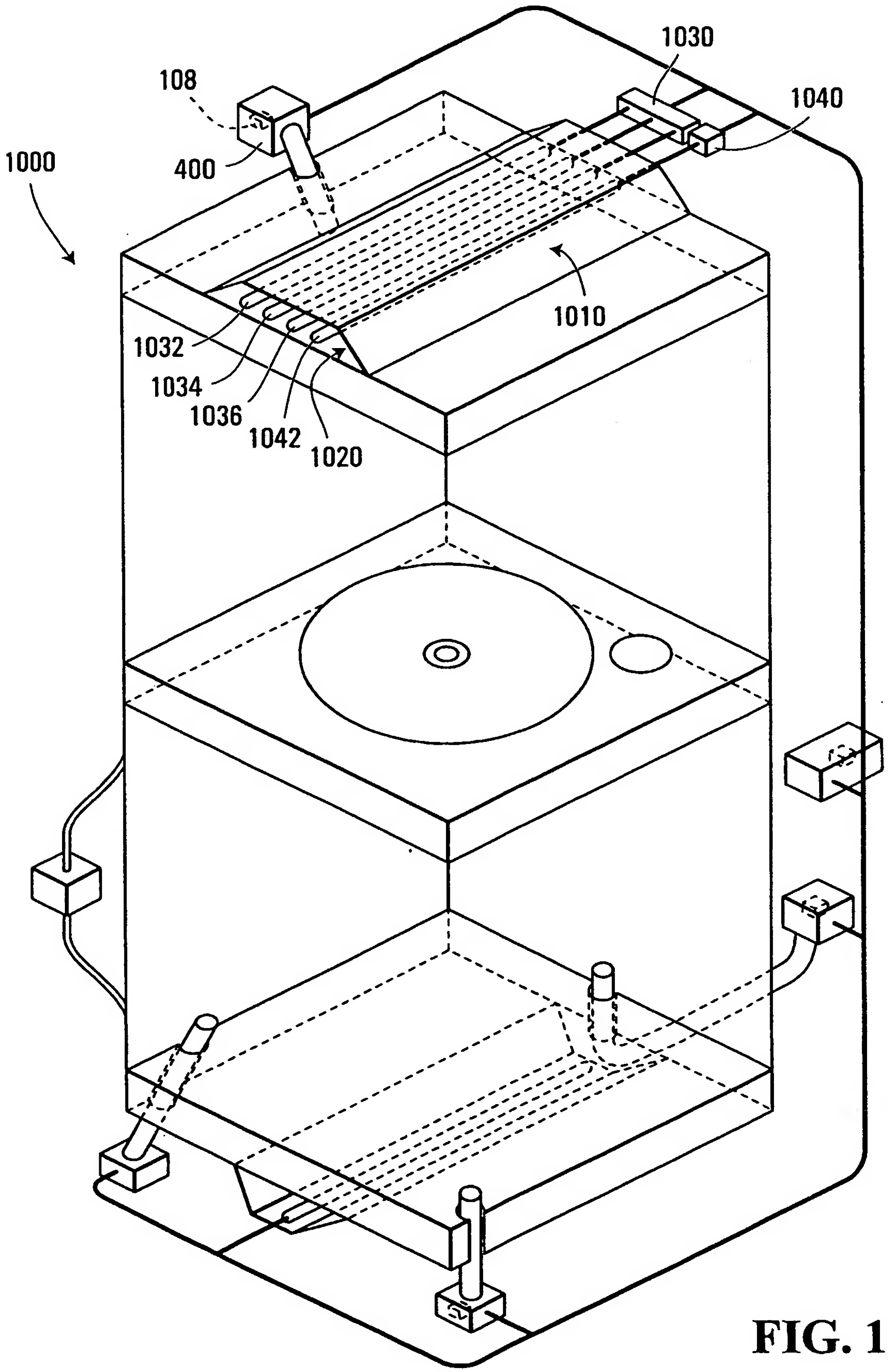


FIG. 13

International Application No
PCT/CA 02/01987

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01J5/10 G01J5/00 H01L21/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01J H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 727 017 A (LERCH WILFRIED ET AL) 10 March 1998 (1998-03-10) abstract column 2, line 64 -column 5, line 50 figures 1,3,5 ---	1-9, 24-28, 31-44, 59-64, 68-73, 76,77, 83,84

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 May 2003	10/06/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Haller, M

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 02/01987

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 942 268 A (ASSOCIATES AG) 15 September 1999 (1999-09-15) abstract paragraphs '0016!-'0027!,'0032!-'0037!,'0048!-'0059!, '0066! figure 1 ---	1-9, 24-28, 31-44, 59-64, 68-73, 76,77, 83,84
X	US 5 308 161 A (STEIN ALEXANDER) 3 May 1994 (1994-05-03) abstract column 3, line 4 -column 4, line 27 figure 1 ---	1-9, 24-28, 31-44, 59-64, 68-73, 76,77, 83,84
A	US 2001/047990 A1 (YOO WOO SIK) 6 December 2001 (2001-12-06) abstract paragraphs '0005!,'!,'0006!,'!,'0012!,'!,'0013!,'!,'0 033!,'!,'0045!,'!,'5060!,'!,'0061! figure 2 ---	4-7, 38-42
A	US 6 171 641 B1 (KOBAYASHI SHIGERU ET AL) 9 January 2001 (2001-01-09) abstract column 13, line 59 -column 14, line 36 ---	6-9, 41-44,77
A	US 5 937 142 A (MESSNER WILLIAM J ET AL) 10 August 1999 (1999-08-10) column 4, line 30 - line 46 column 12, line 52 -column 13, line 24 column 14, line 59 -column 15, line 12 figures 14,19 ---	72,73
A	DE 42 23 133 A (T ELEKTRONIK GMBH AS) 21 January 1993 (1993-01-21) abstract column 3, line 50 -column 7, line 59 ---	10-23, 29,30, 45-58, 65-67, 74,75, 78-82

-/--

International Application No
PCT/CA 02/01987

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 1997, no. 02, 28 February 1997 (1997-02-28) & JP 08 261967 A (CHIYOUKOUON ZAIRYO KENKYUSHO:KK;YAMAGUCHI PREF GOV SANGYO GIJUTSU KAIH), 11 October 1996 (1996-10-11) abstract ---	10,11, 13,45, 46,48, 78,79
A	US 4 979 134 A (ARIMA JIRO ET AL) 18 December 1990 (1990-12-18) column 3, line 28 -column 4, line 29 column 6, line 49 -column 8, line 22 figures 1,3 -----	10,45,78

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5727017 A	10-03-1998	DE 19513749 A1	24-10-1996
EP 0942268 A	15-09-1999	US 6056434 A	02-05-2000
		EP 0942268 A1	15-09-1999
		JP 11316159 A	16-11-1999
US 5308161 A	03-05-1994	NONE	
US 2001047990 A1	06-12-2001	US 6337467 B1	08-01-2002
		WO 03009350 A2	30-01-2003
		EP 1203399 A1	08-05-2002
		WO 0186702 A1	15-11-2001
US 6171641 B1	09-01-2001	US 5707500 A	13-01-1998
		DE 4092221 C2	21-04-1994
		DE 4092221 T	30-01-1992
		WO 9109148 A1	27-06-1991
		JP 2923008 B2	26-07-1999
		JP 3232968 A	16-10-1991
		JP 3244462 B2	07-01-2002
		JP 10140349 A	26-05-1998
		JP 3244463 B2	07-01-2002
		JP 10140350 A	26-05-1998
		KR 9407608 B1	22-08-1994
		US 5815396 A	29-09-1998
US 5937142 A	10-08-1999	US 6108490 A	22-08-2000
		US 6167195 A	26-12-2000
DE 4223133 A	21-01-1993	DE 4223133 A1	21-01-1993
		US 5359693 A	25-10-1994
JP 08261967 A	11-10-1996	NONE	
US 4979134 A	18-12-1990	JP 2256254 A	17-10-1990
		KR 9613995 B1	11-10-1996